

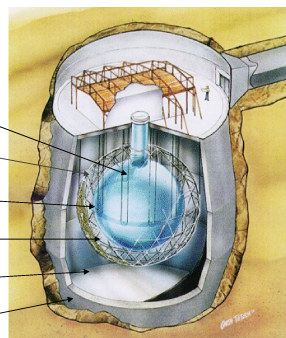
# Particle Physics and Cosmology

## — New Melting Pot —

Hitoshi Murayama

Director's Review on Physics Division, Nov 10, 2004



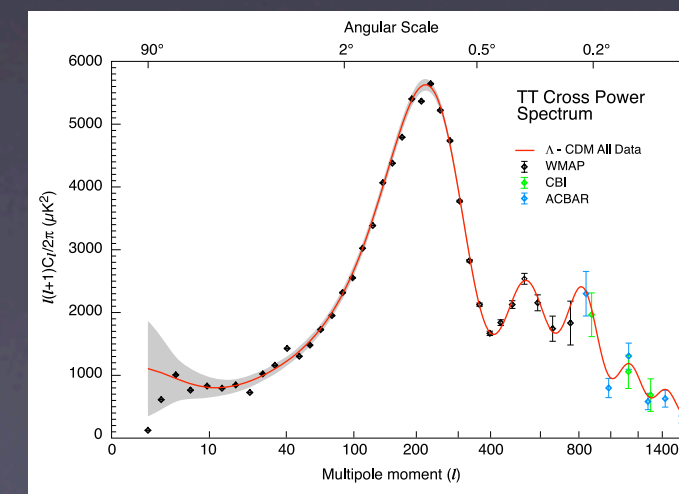
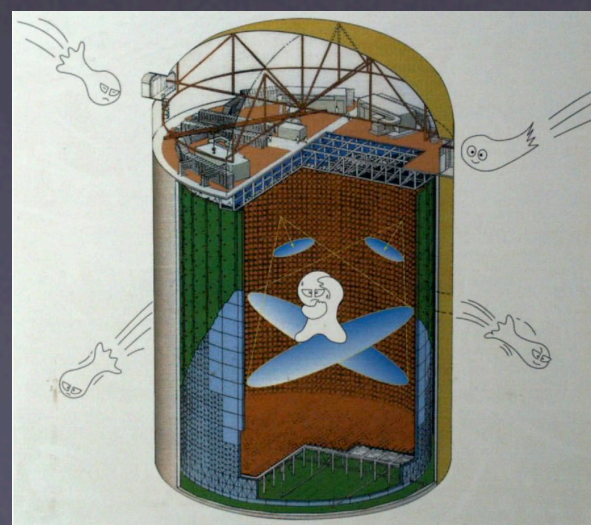
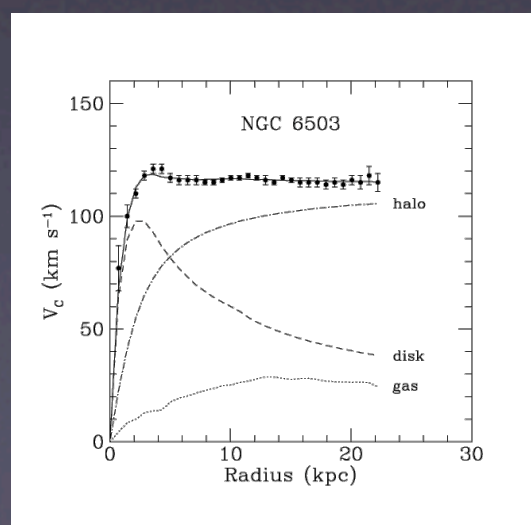
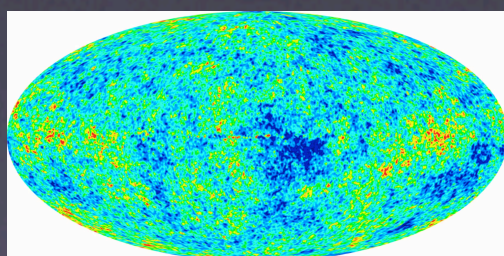
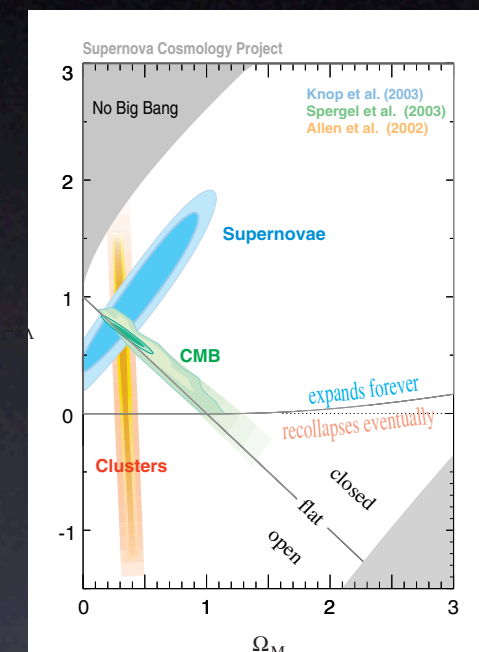
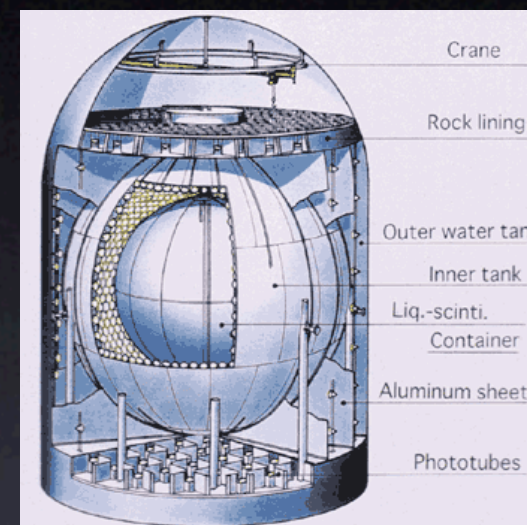
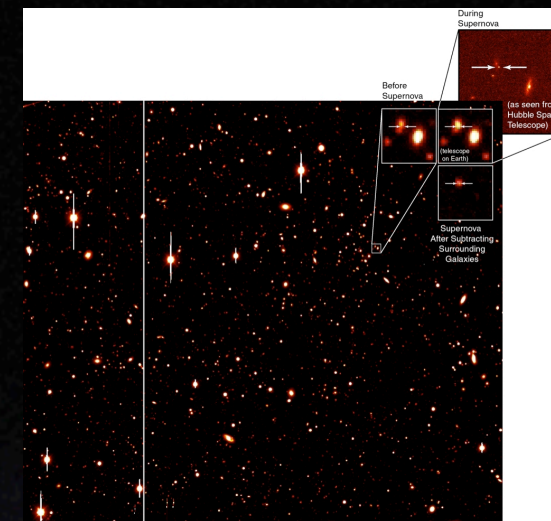


# Exciting time

## New discoveries:

- Dark Matter
- Dark Energy
- Neutrino oscillation
- Scale-invariant density fluctuation

We have to at least address these!





# Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Dark Field (Higgs)  $\sim 10^{62}\%$ ??





# Cosmic Questions

*What is the nature of the universe and what is it made of?*

*What are matter, energy, space and time?*

*How did we get here and where are we going?*

*(HEPAP Quantum Universe Report)*

*We have a commanding knowledge of ordinary matter*

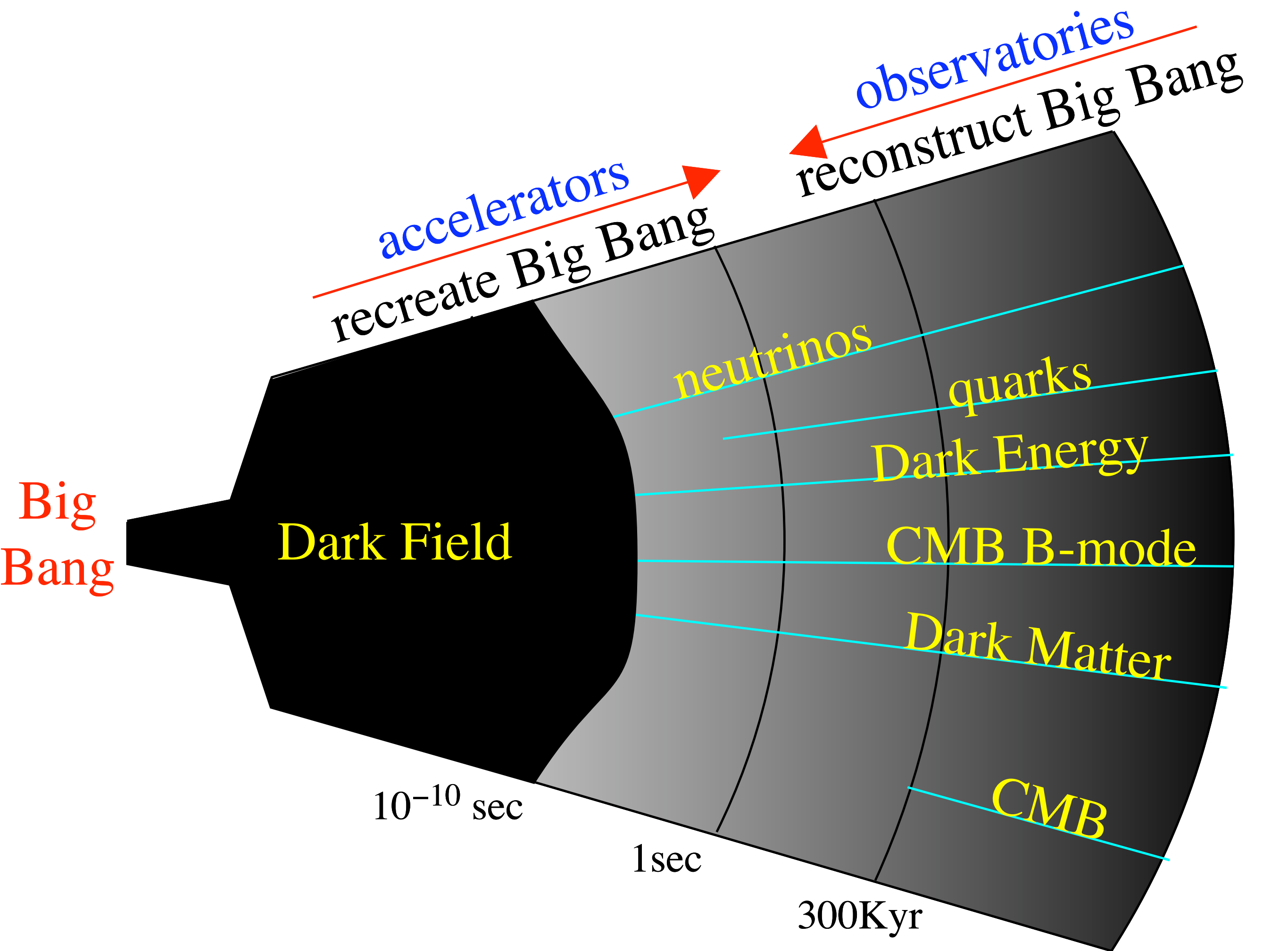
- We don't know what 95% of the Universe is made of!
- We still can't relate gravity and QM

*We have convergence of*

- Experimental surprises
- Theoretical developments
- Success of the Standard Model

*To us, cosmology and particle physics are synonymous*





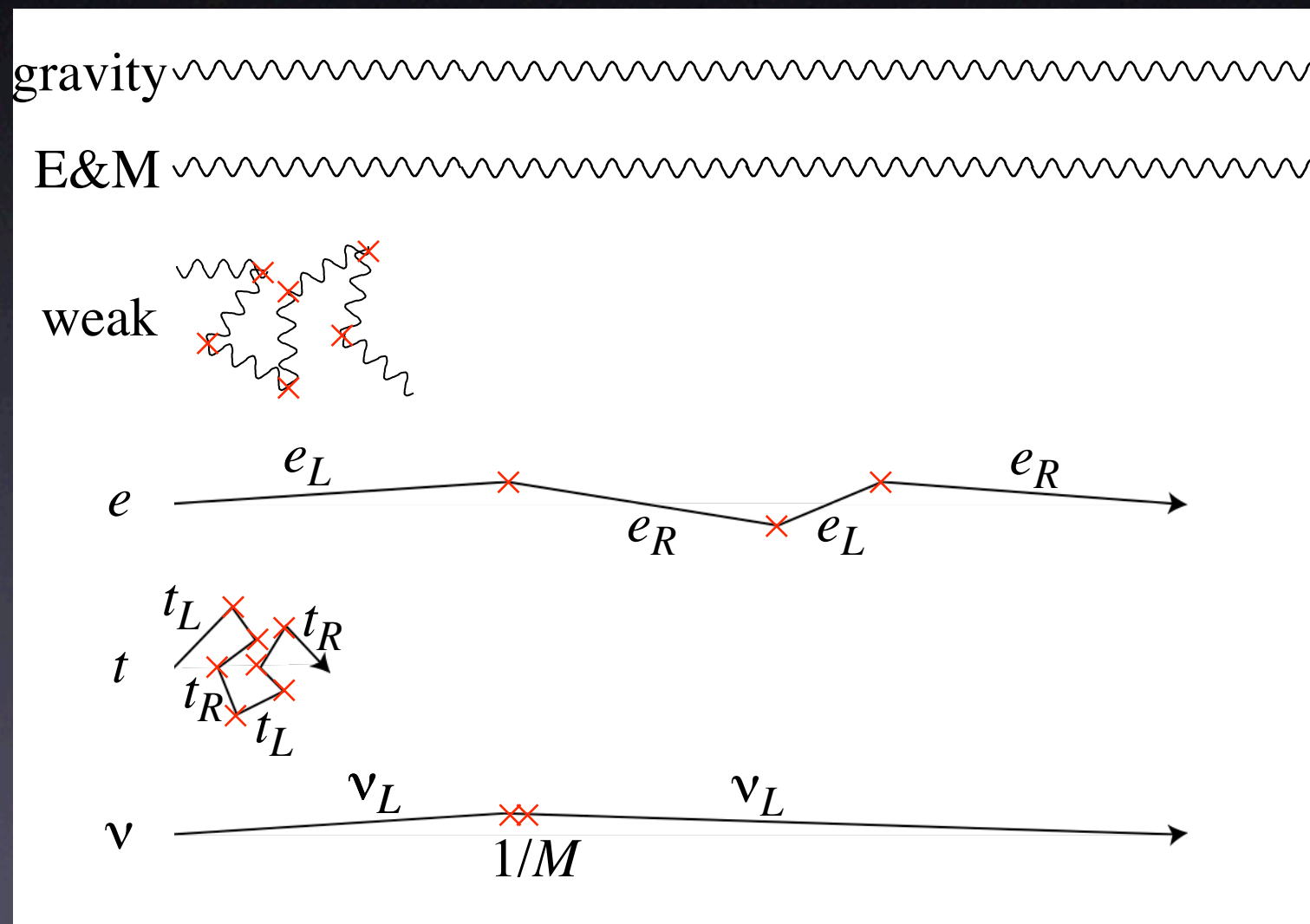


Dark Field  
=Cosmic BEC



# We are swimming in a BEC

- There is something filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- What is it??





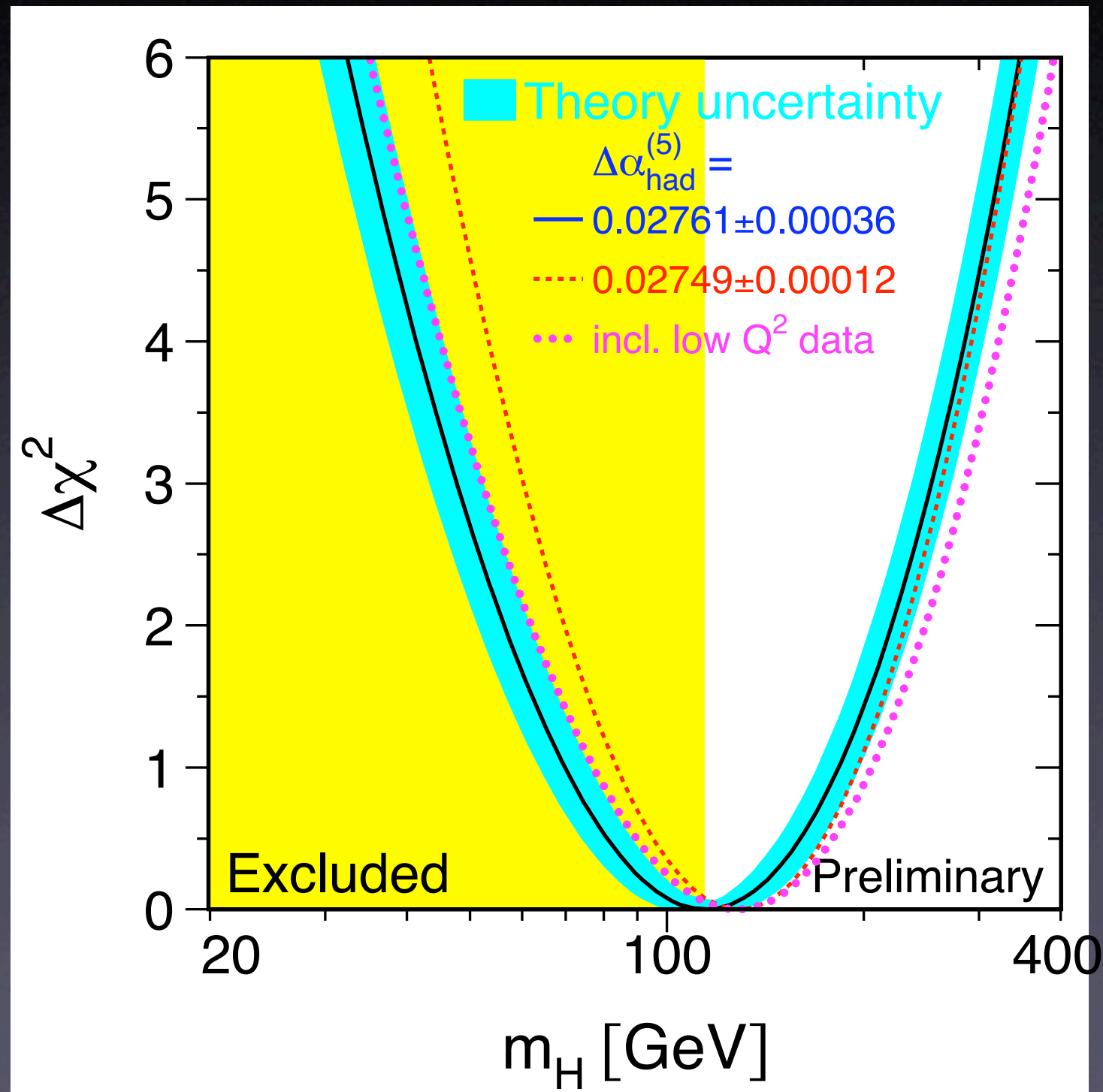
# Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the “penetration length”  
⇒ Magnetic field is short-ranged!
- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her “Universe”
  - But doesn’t know what the condensate is, nor why it condenses
  - Doesn’t have enough energy (gap) to break up Cooper pairs

That’s the stage where we are!

# Gap Excitation

- We know the energy scale of the problem:  
 $G_F \approx (300 \text{ GeV})^{-2}$
- the gap excitation is called “Higgs boson”
- Current data combined with the Standard Model theory predict  
 $m_H < 260 \text{ GeV}$  (95%CL)





# Solving the Dark Field Problem

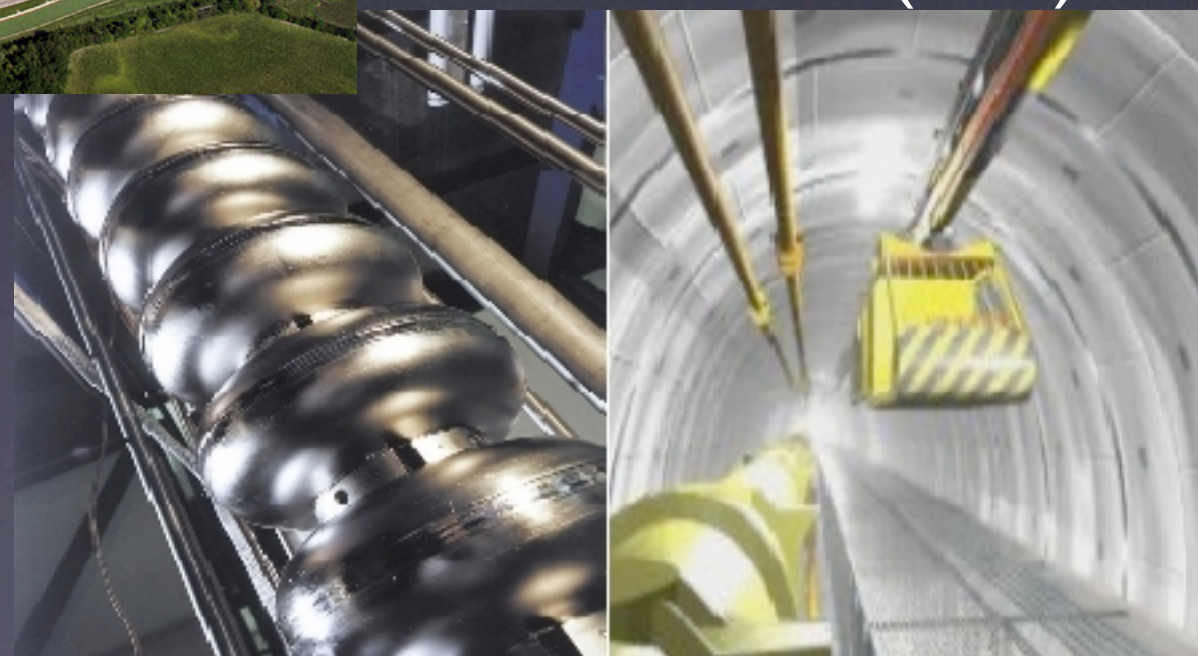


Tevatron

Large Hadron Collider (LHC)

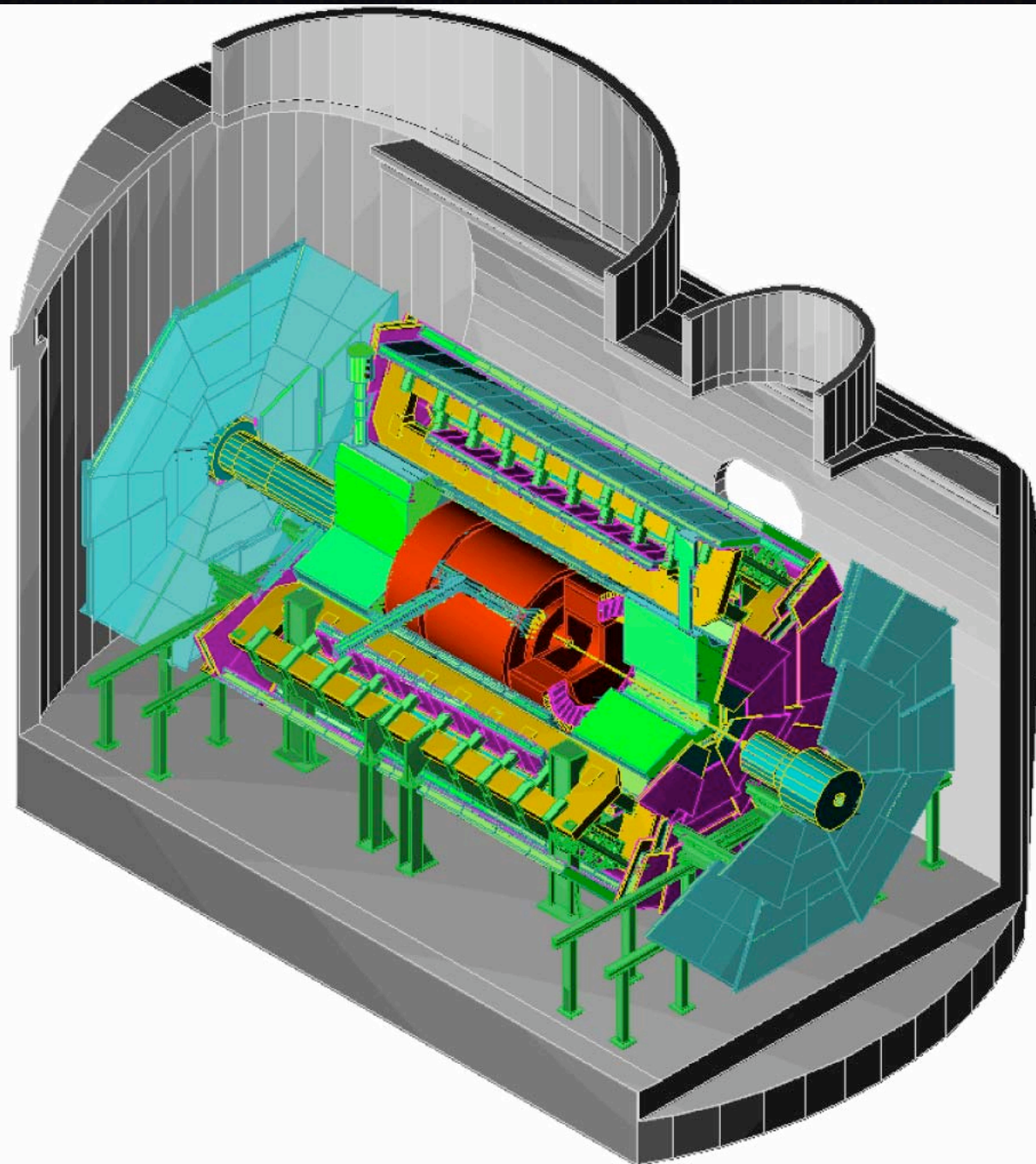


International Linear Collider (ILC)

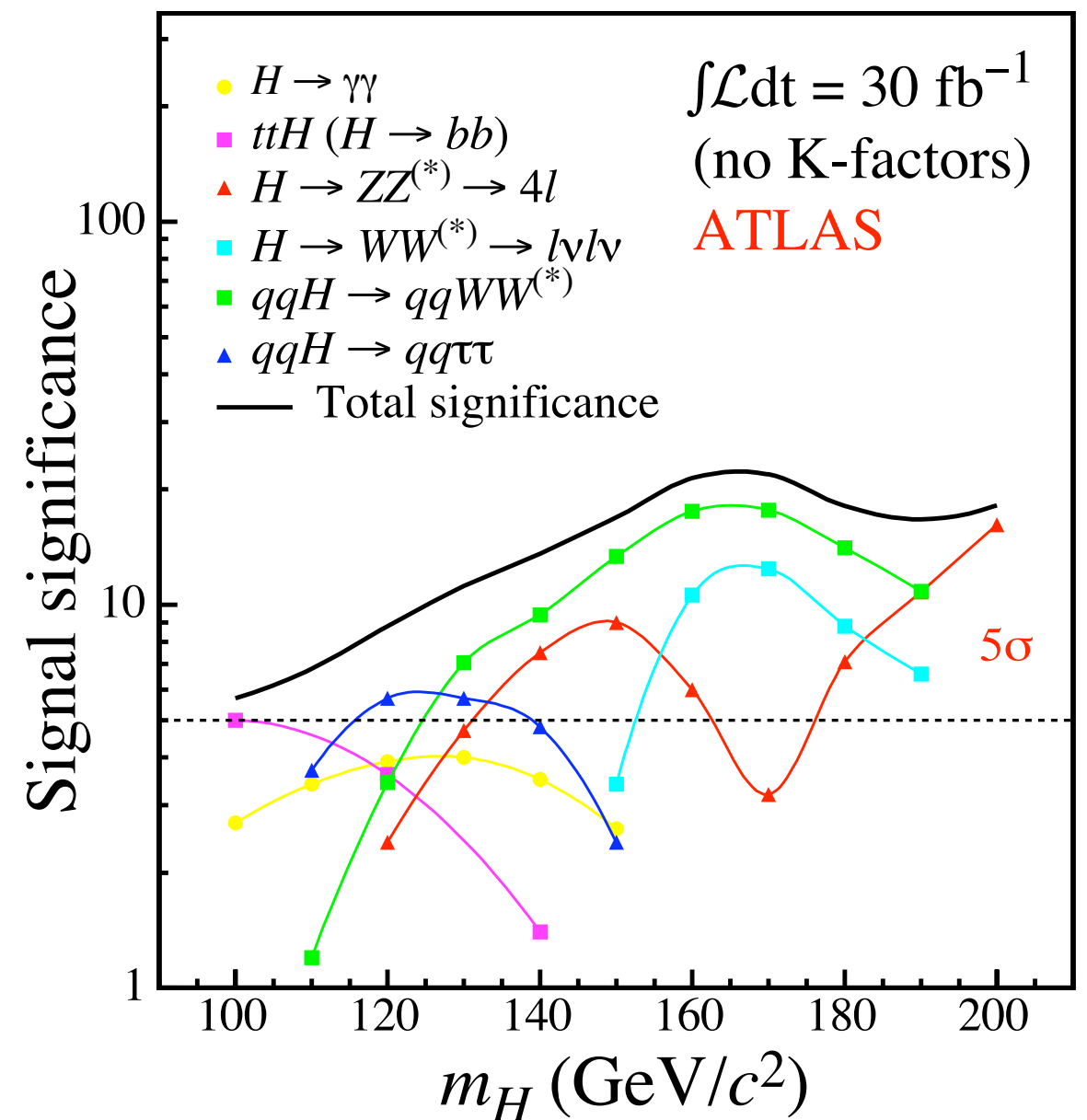




# Higgs at ATLAS



## Robust discovery





# Post-Higgs Problem

- We see “what” is condensed
- But we still don’t know “why”
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation  
 $\sim \text{TeV} \ll M_{\text{Pl}} = 10^{15} \text{TeV}$
- Explanation most likely to be at  $\sim \text{TeV}$  scale because this is the relevant energy scale

# Three Directions

## History repeats itself

- Crisis with electron solved by anti-matter
- Double #particles again  $\Rightarrow$  supersymmetry

## Learn from Cooper pairs

- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite  
 $\Rightarrow$  technicolor

## Physics as we know it ends at TeV

- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV  
 $\Rightarrow$  hidden dimensions (0.01 cm to  $10^{-17}$  cm)



# More Directions

- Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)
- Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)
- Fat Higgs (Composite)
- Higgsless and  $W^\pm$  as Kaluza-Klein boson
- technicolorful supersymmetry



THOUGHT OF

NOT YET

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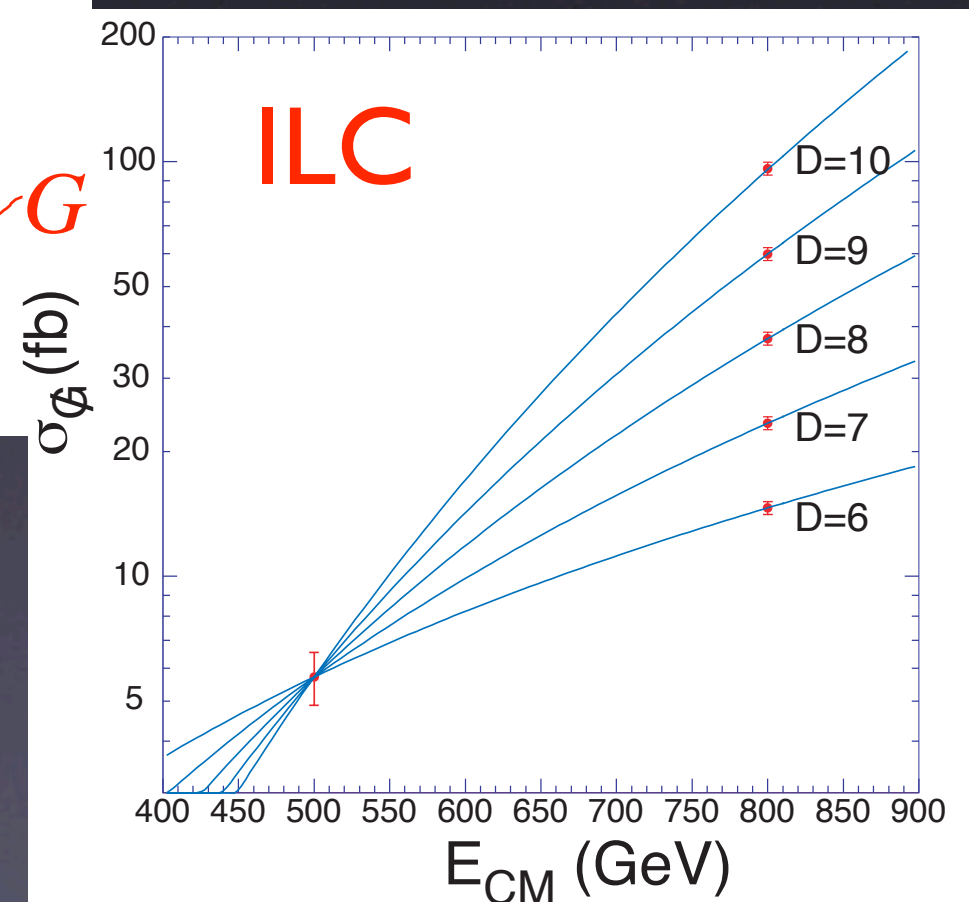
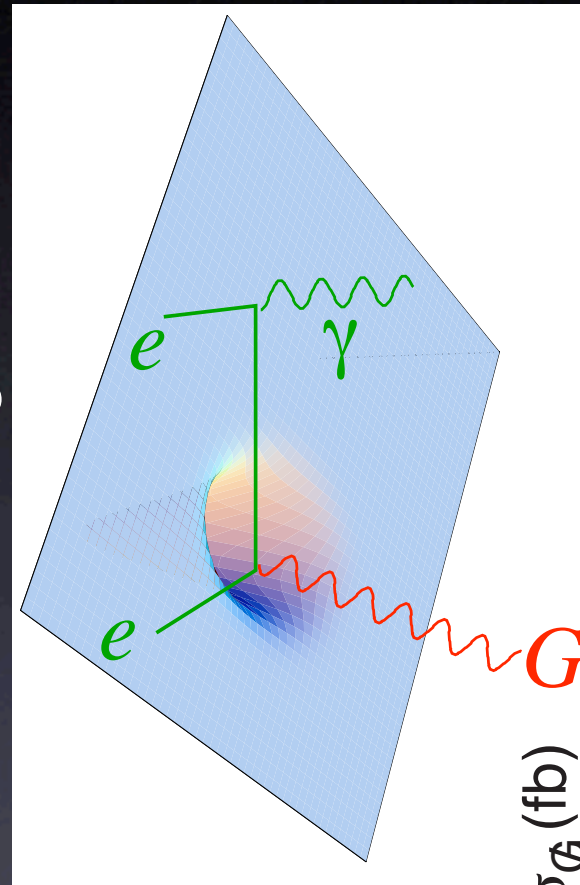


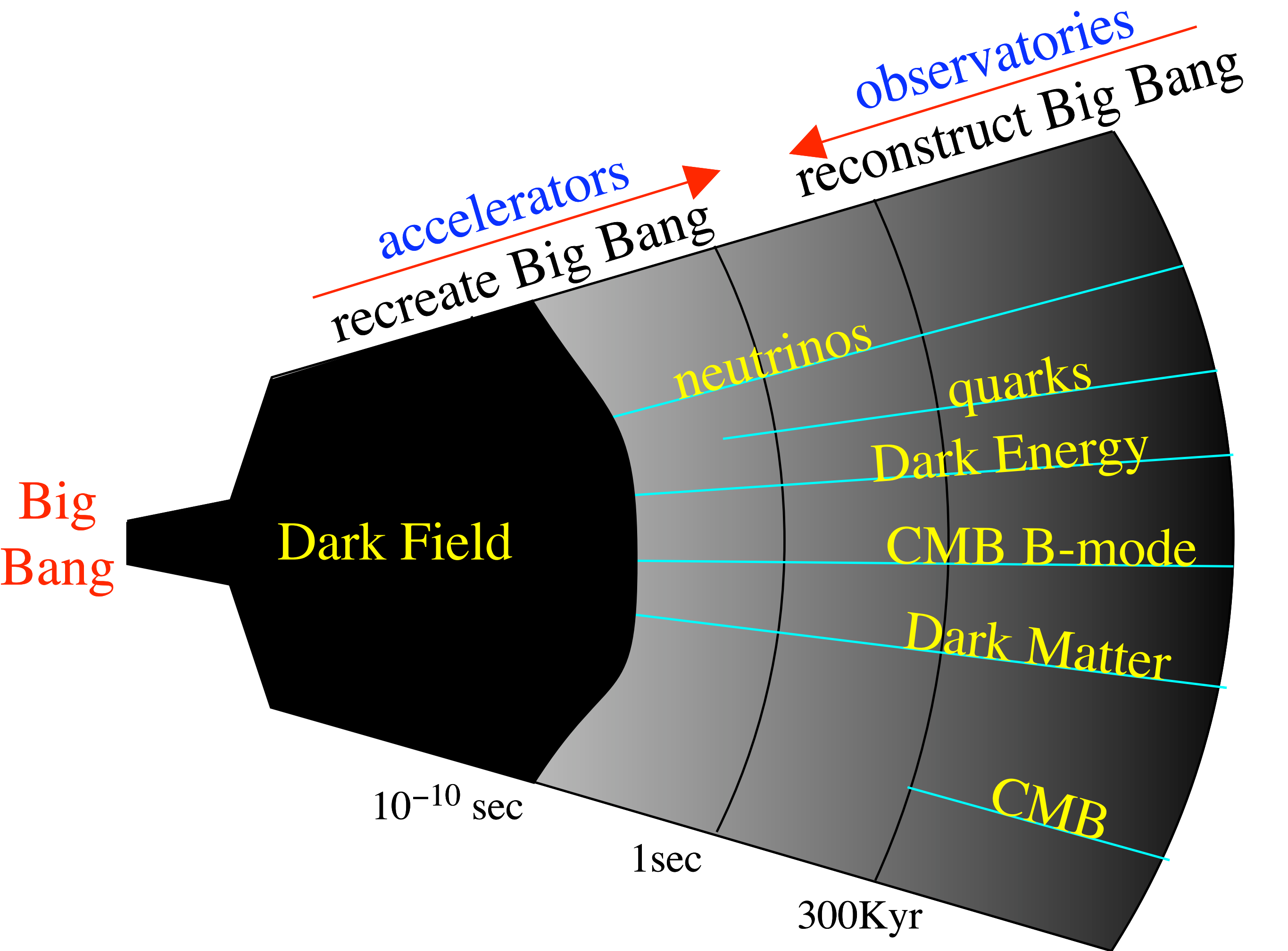


# Hidden Dimensions

- Hidden dimensions
- Can emit graviton into the bulk
- Events with apparent energy imbalance

⇒ How many extra dimensions are there?



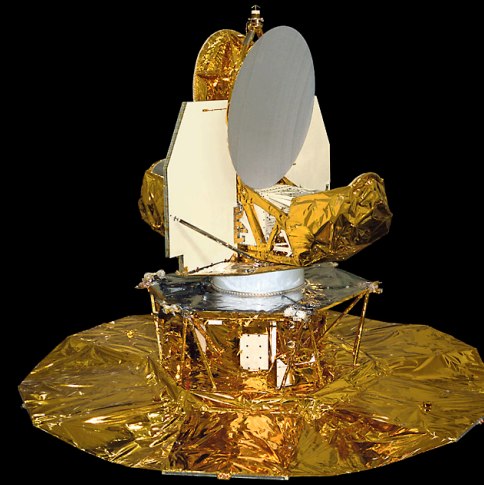




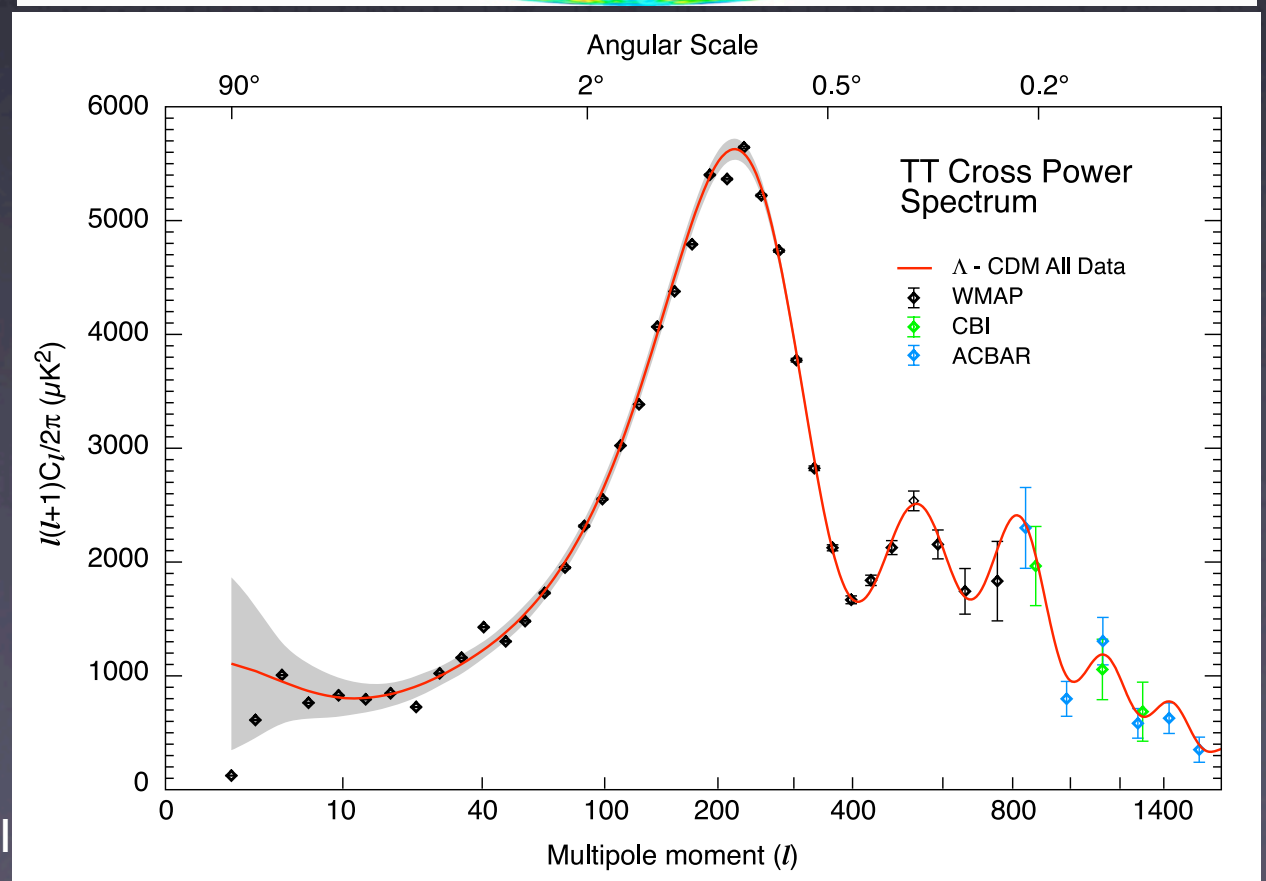
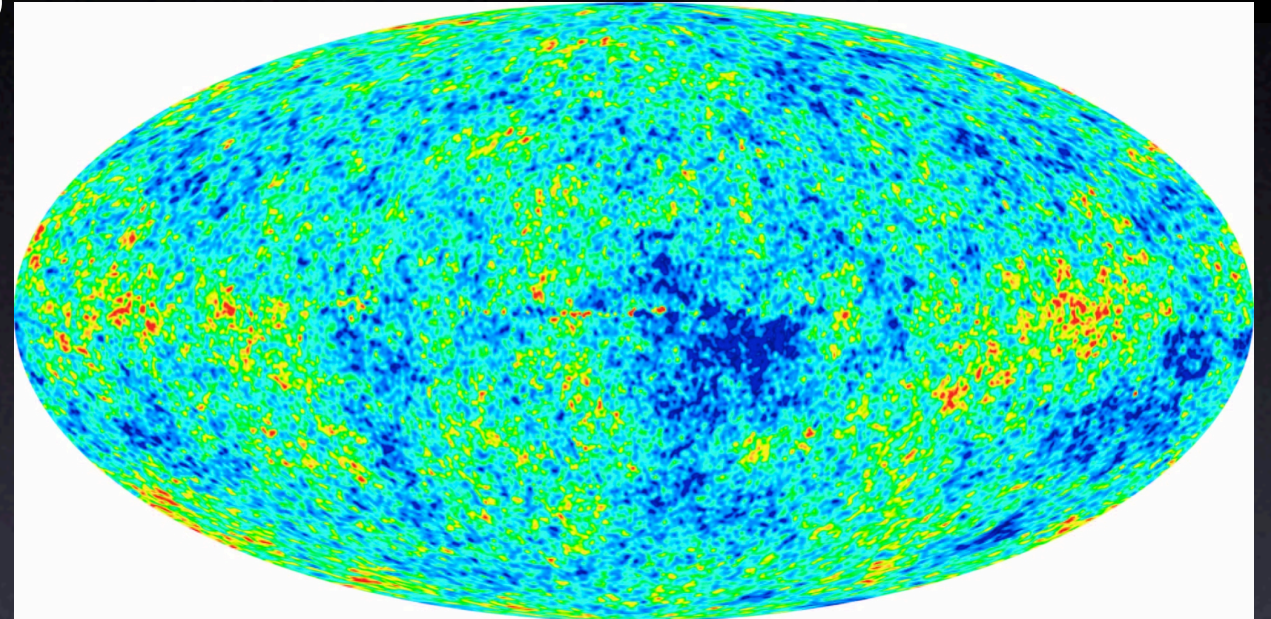
# Dark Matter



# Cosmic Microwave Background



- Pioneered by COBE, MAXIMA
- WMAP result:  
 $h=0.71\pm0.04$   
 $\Omega_M h^2=0.135\pm0.009$   
 $\Omega_b h^2=0.0224\pm0.0009$   
 $\Omega_{\text{tot}}=1.02\pm0.02$
- $>12\sigma$  signal for exotic dark matter

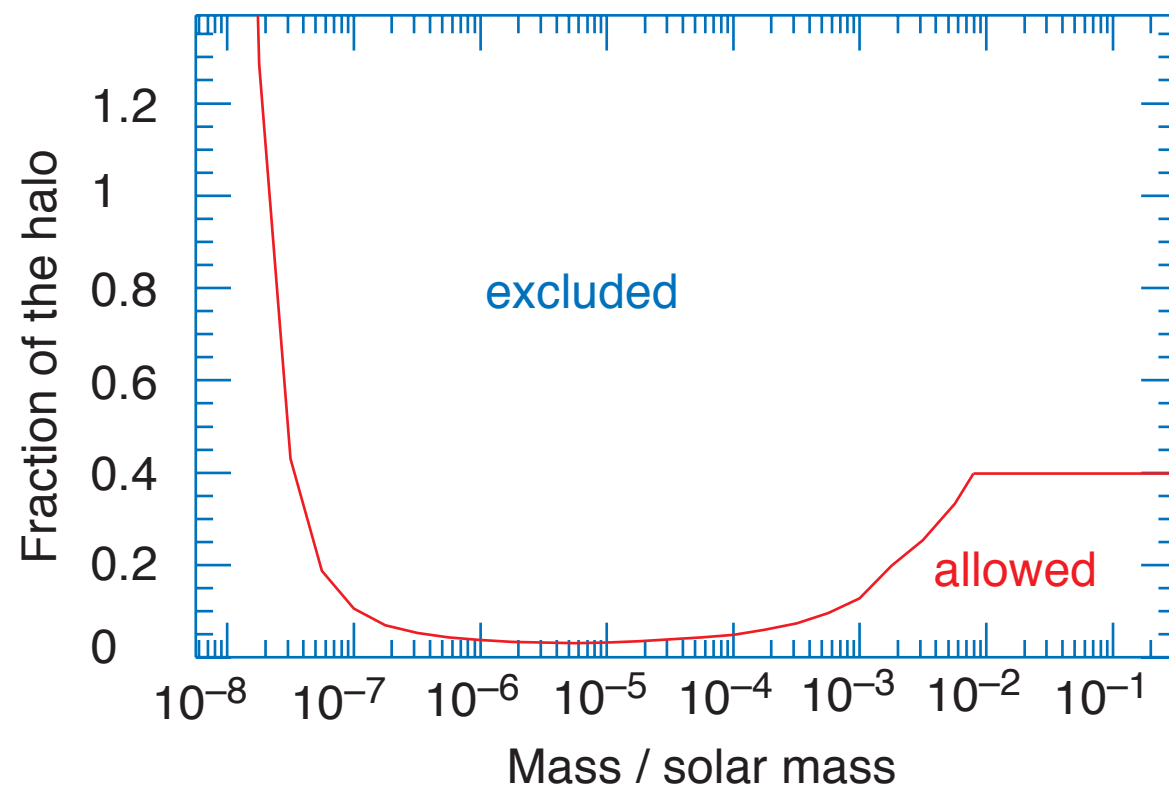




# Particle Dark Matter

It is not dim small stars  
(e.g., MACHOs)

- **WIMP** (Weakly Interacting Massive Particle) **strongly favored**
- Stable heavy particle produced in early Universe, **left-over from near-complete annihilation**

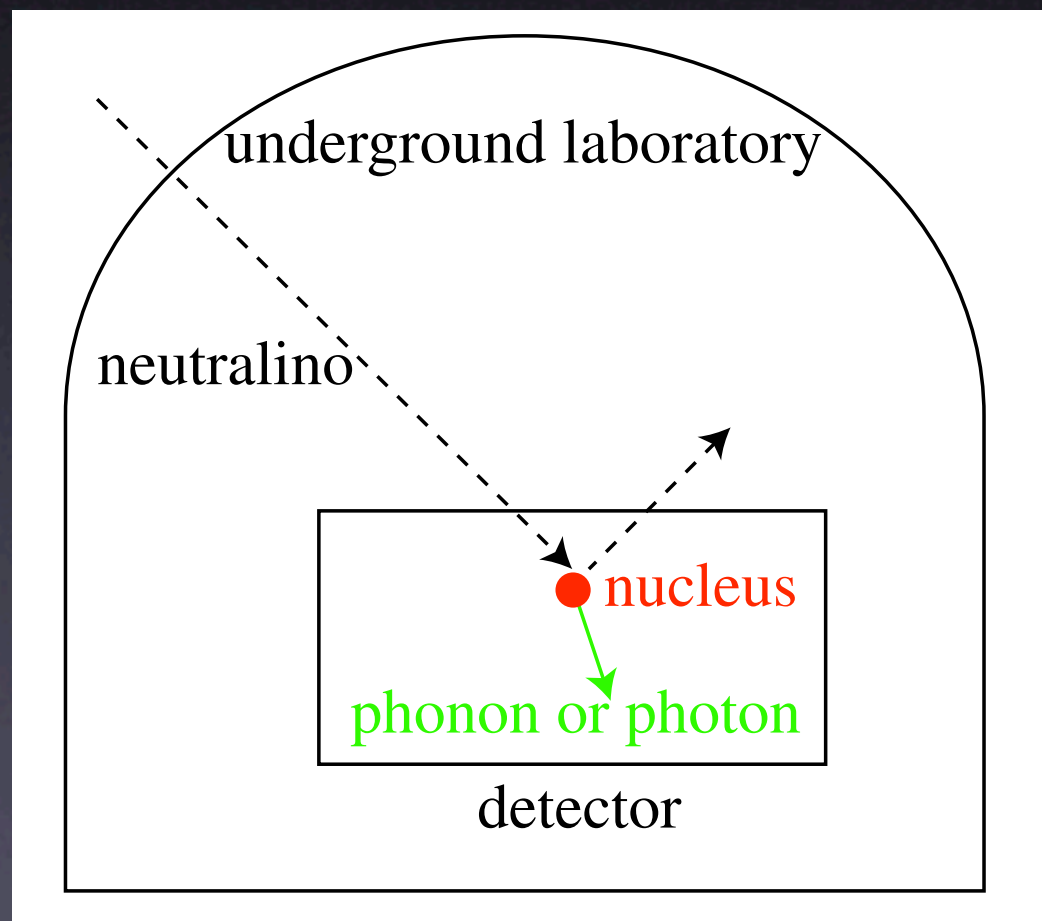


- $$\Omega_M \simeq 0.23 \frac{\pi \alpha^2 / \text{TeV}^2}{\sigma_{ann}}$$
- **TeV =  $10^{12}$  eV** the correct energy scale

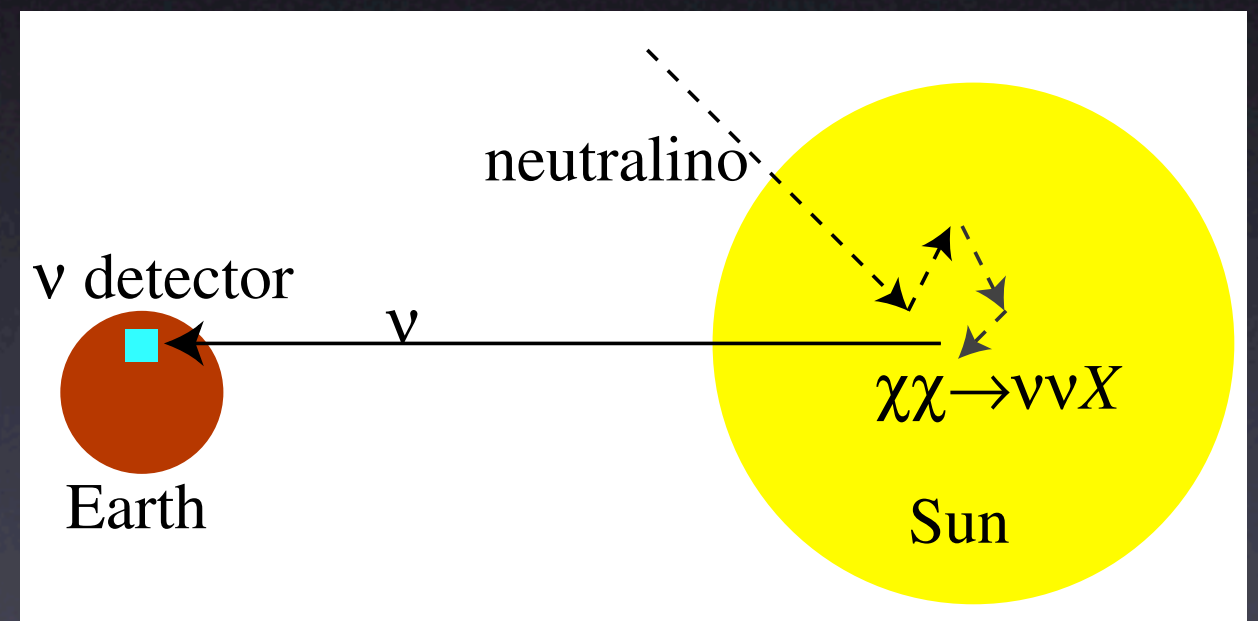


# Detection of Dark Matter

- Direct detection
- **CDMS-II**



- Indirect detection
- **AMANDA, Icecube**



complementary techniques  
are getting into the interesting  
region of parameter space

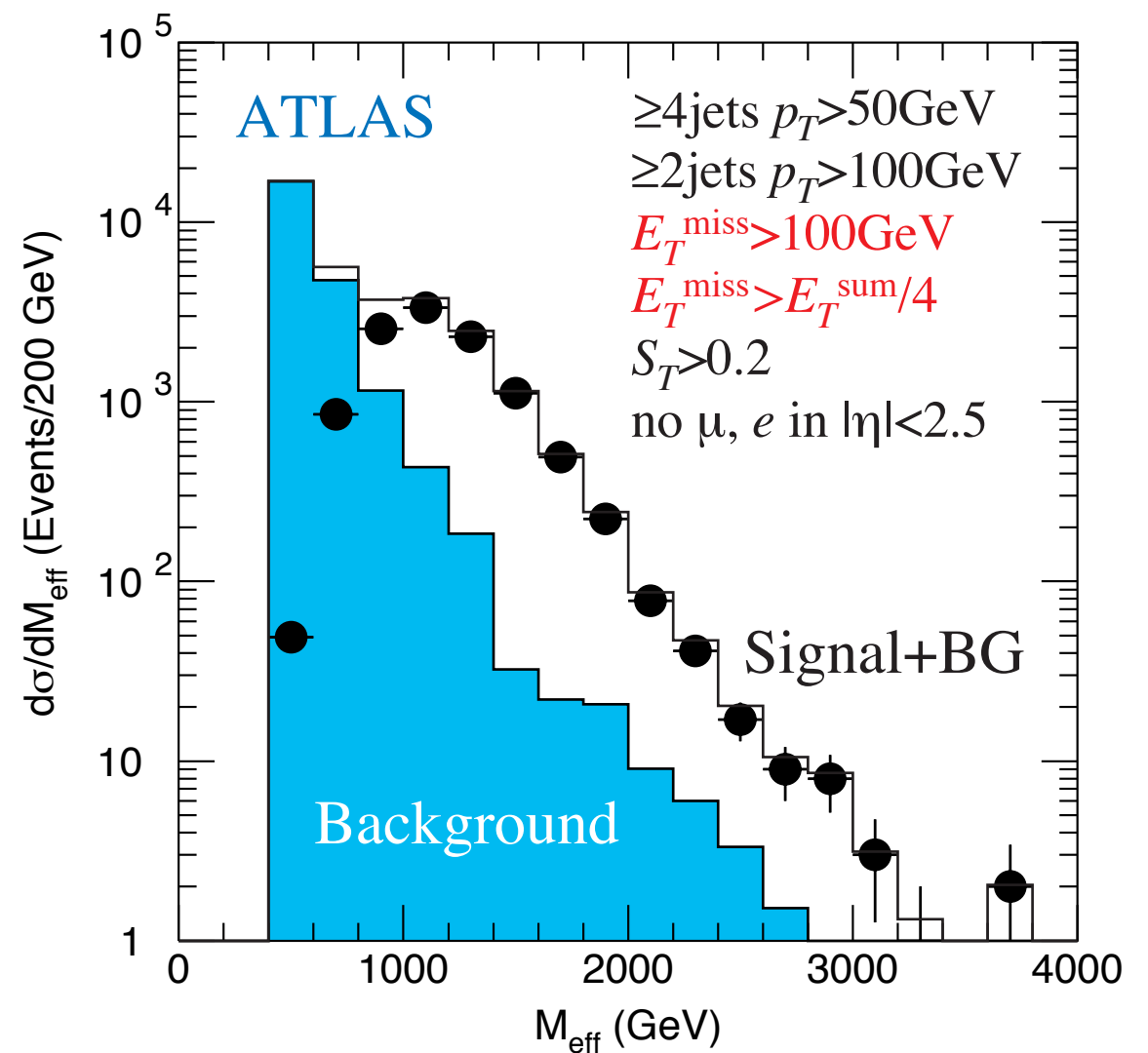
- Detect Dark Matter to see **it is there**.
- Will not tell us **what it is**.



# Producing Dark Matter at LHC

- Look for events where energy and momenta are unbalanced  
“missing energy”  $E_{\text{miss}}$
- Something is escaping the detector
- electrically neutral, weakly interacting  
 $\Rightarrow$  Dark Matter!?

## Supersymmetric Dark Matter



# How do we know what Dark Matter *is*?

- cosmological measurement of dark matter

- abundance  $\propto \sigma_{\text{ann}}^{-1}$

- detection experiments

- scattering cross section

- production at colliders

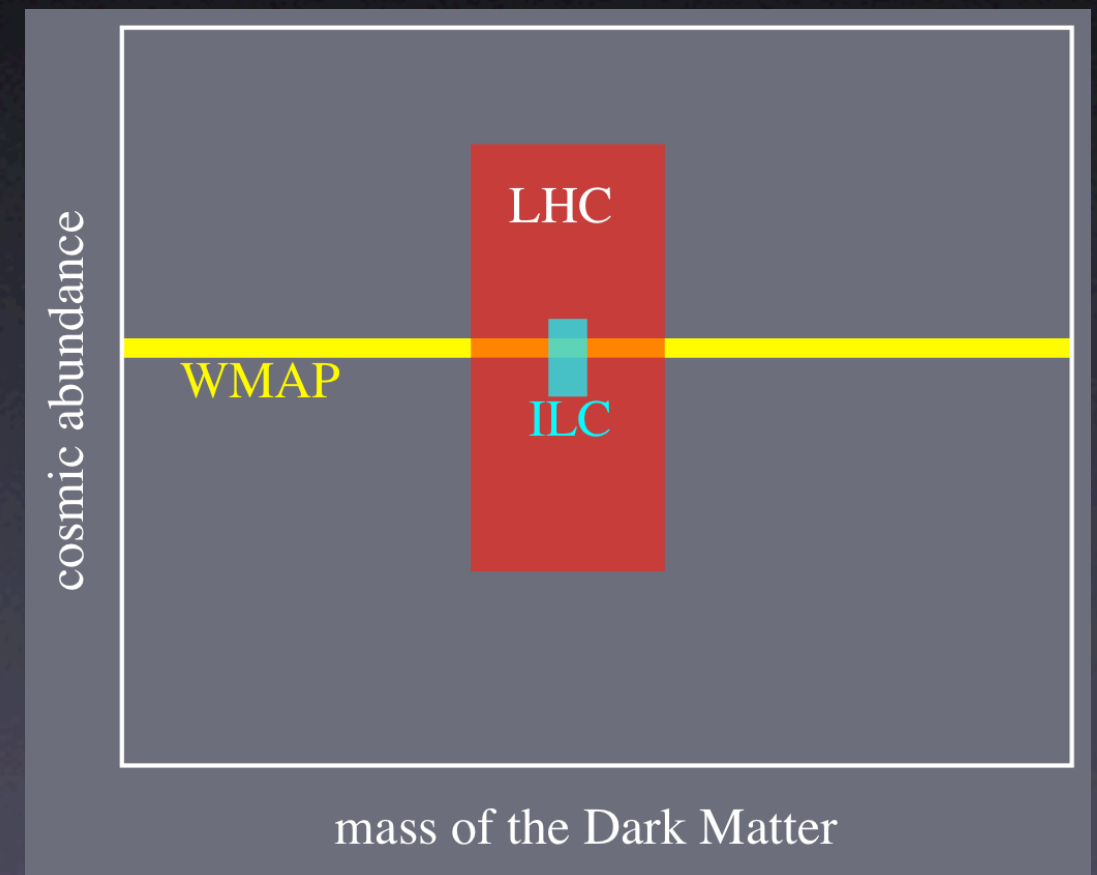
- mass, couplings

- can calculate cross sections

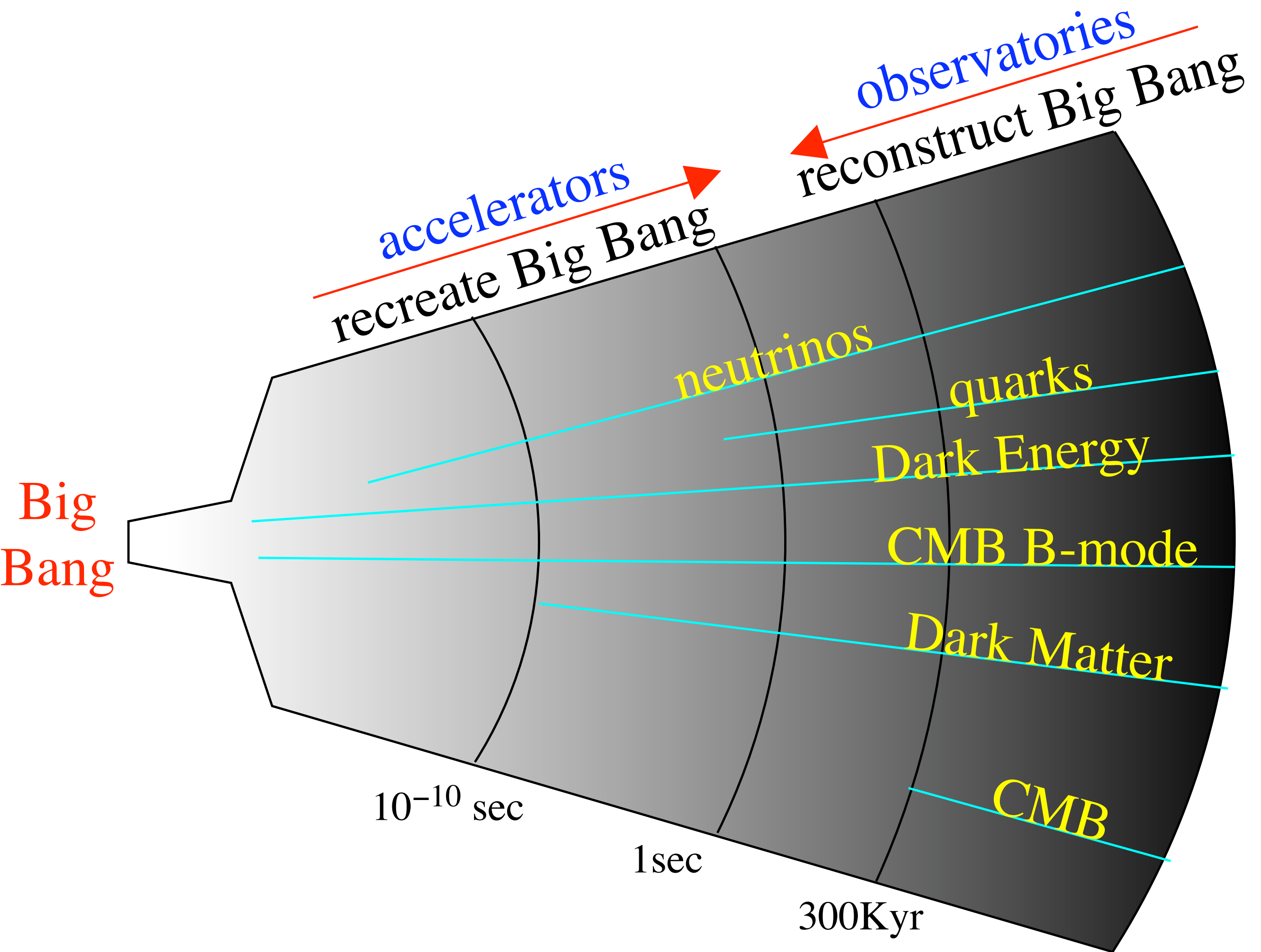
- If they agree with each other:

⇒ Will know *what Dark Matter is*

⇒ Will understand universe back to  $t \sim 10^{-10}$  sec







# Anti-Matter



# Matter and Anti-Matter

## Early Universe

10,000,000,001

10,000,000,000

$q$

$\bar{q}$

# Matter and Anti-Matter Current Universe

|  
•  
us

$q$

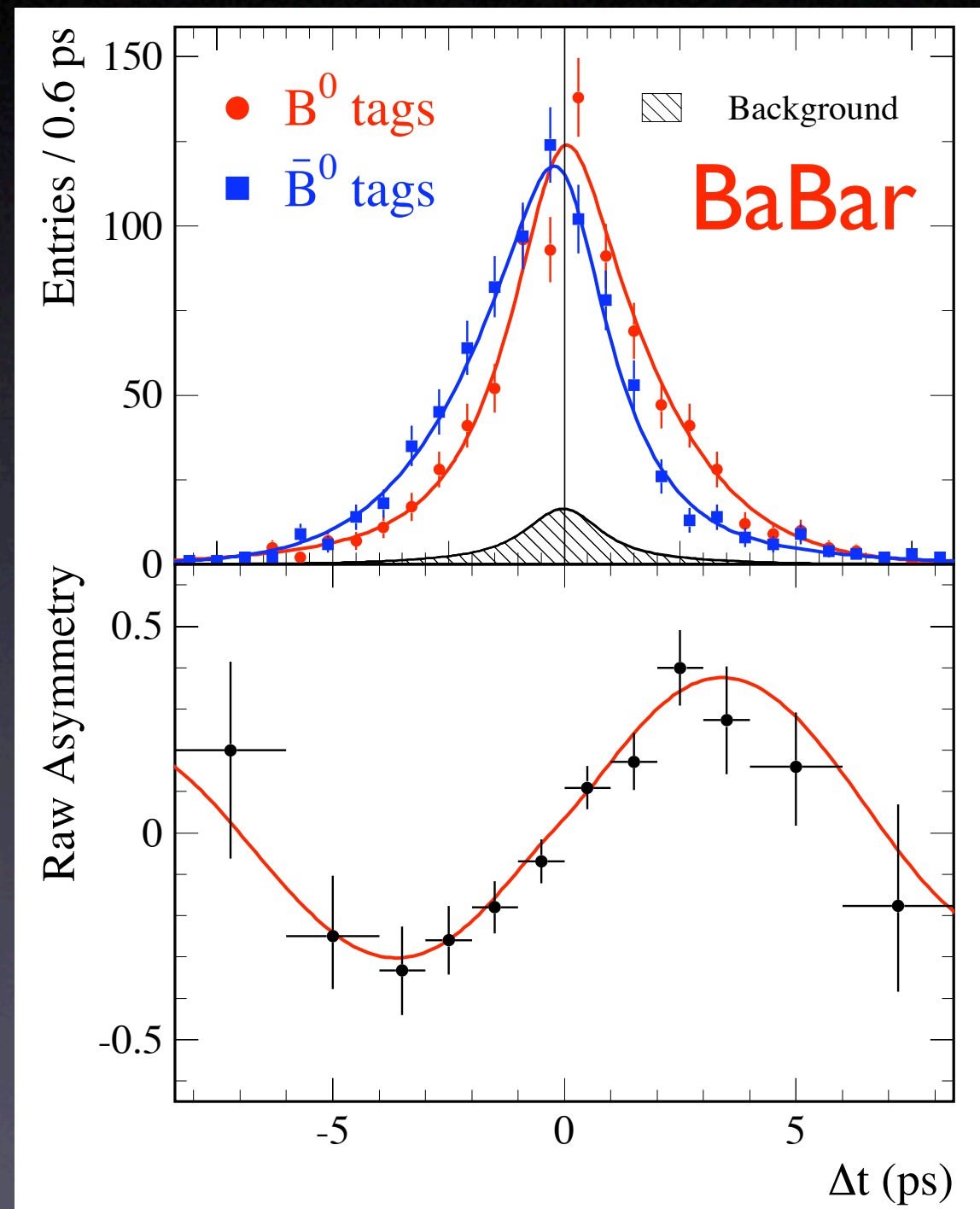
$\bar{q}$

The Great Annihilation



# CP Violation

- Is anti-matter the exact mirror of matter?  
1964 discovery of CP violation in neutral kaon system
- But only one system, hard to tell what is going on.  
2001 Found kaon and anti-kaon decay differently at  $10^{-6}$  level
- 2002 Found CP violation also in B-meson system
- But no CP violation observed so far is not large enough to explain the absence of anti-matter



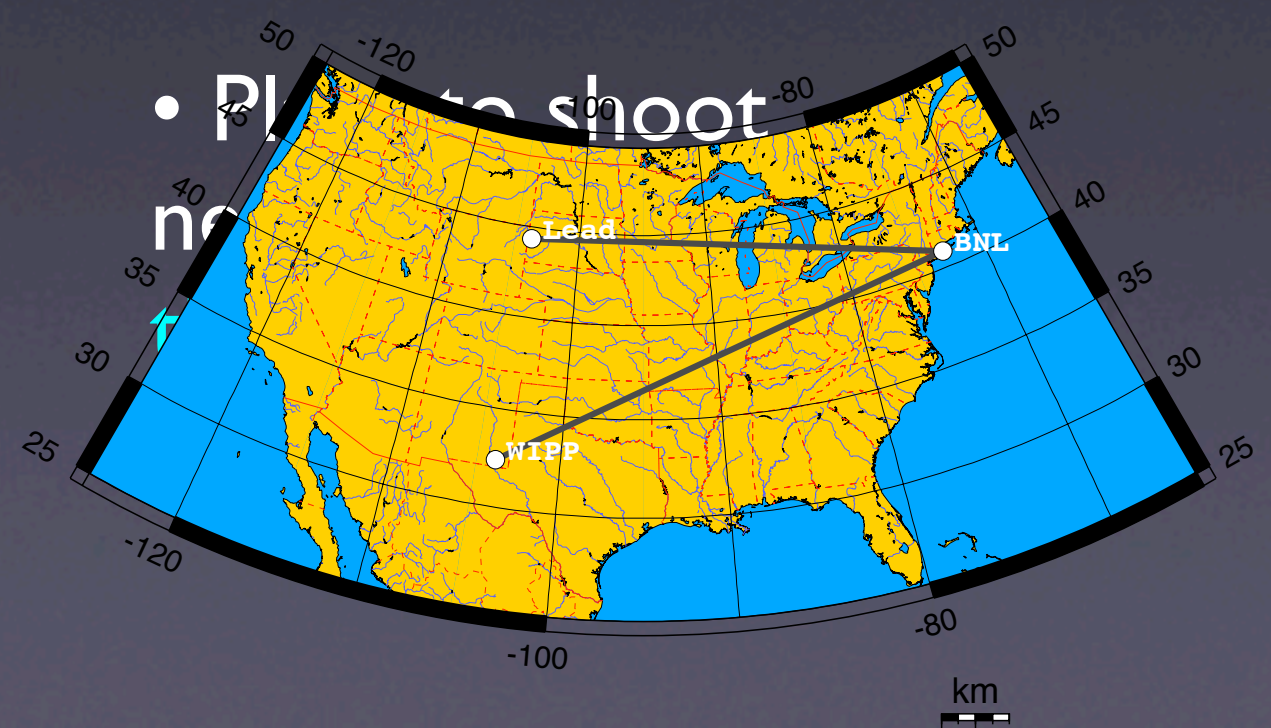
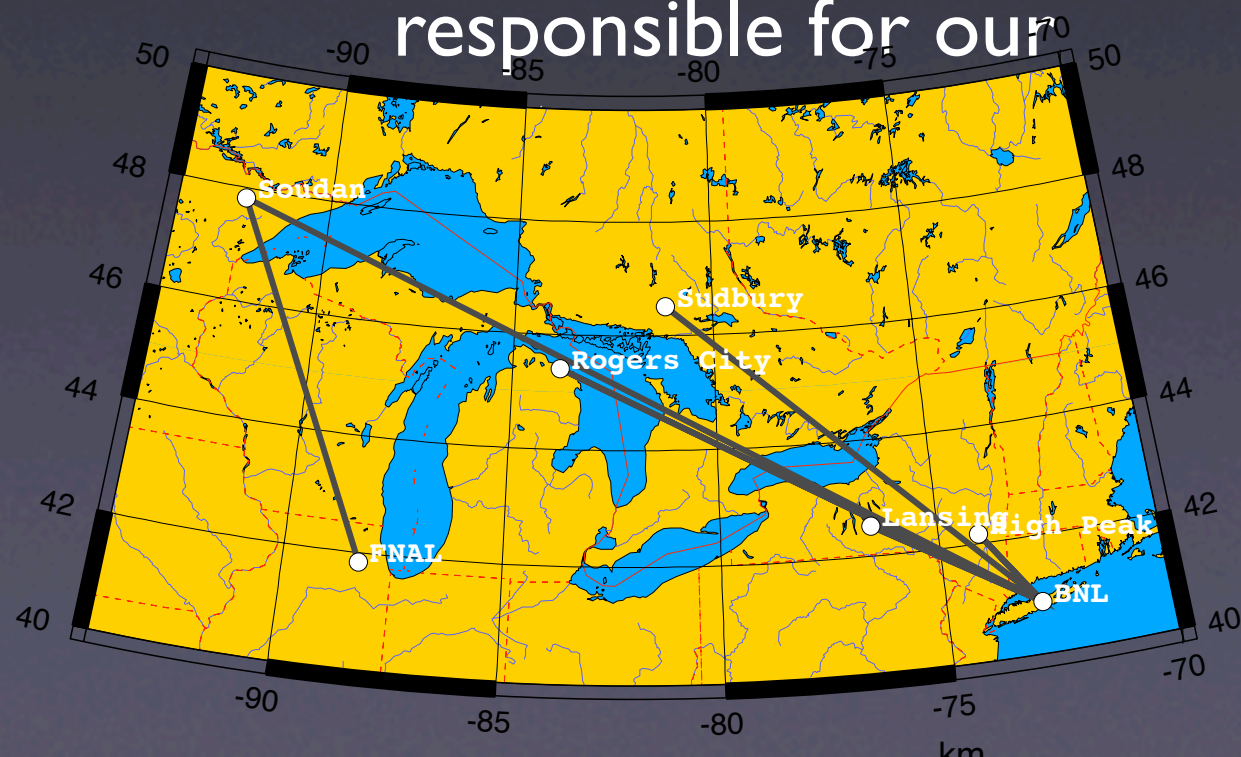
# Leptogenesis

- Neutrinos have mass
- Neutrinos may be **their own anti-particles**
- They can **transform matter to anti-matter** and vice versa
- Maybe they are responsible for our

- CP-violation may be observed in neutrino oscillation

only unknown

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16s_{12}c_{12}s_{13}^2c_{13}^2s_{23}c_{23} \sin \delta \sin \left( \frac{\Delta m_{12}^2 L}{4E} \right) \sin \left( \frac{\Delta m_{13}^2 L}{4E} \right) \sin \left( \frac{\Delta m_{23}^2 L}{4E} \right)$$

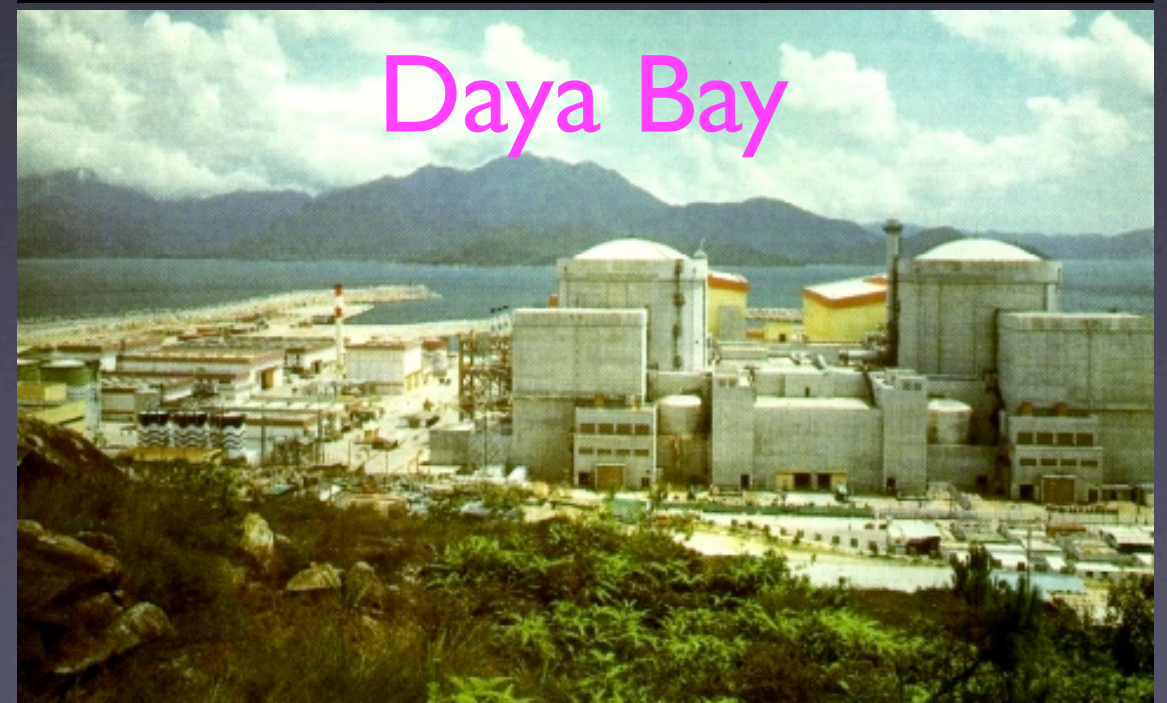


- Please shoot me



# $\theta_{13}$ decides the future

- The value of  $\theta_{13}$  crucial for the future of neutrino oscillation physics
- Determines the required facility/parameters/baseline/energy
- Two paths to determine  $\theta_{13}$ 
  - Long-baseline accelerator  $\nu$  oscillation
  - Reactor  $\nu$  experiment with  $\geq$ two detectors

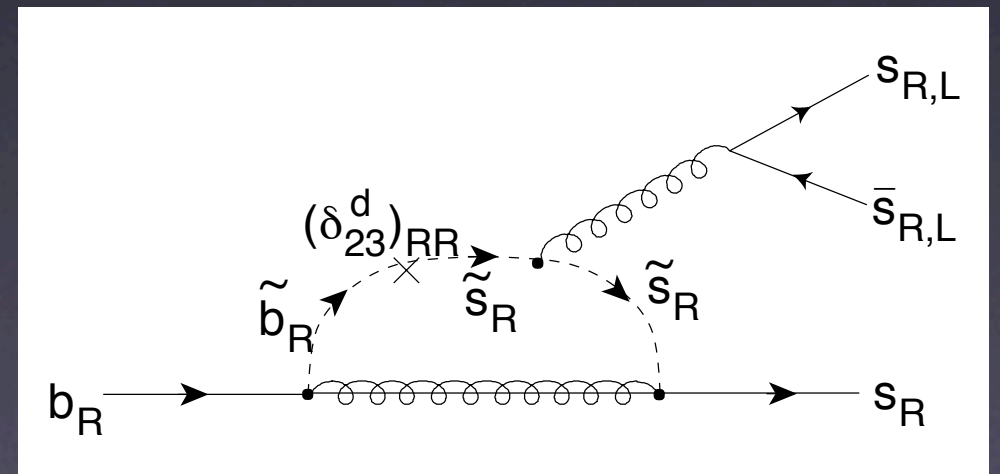




# Large $\theta_{23}$ and quarks

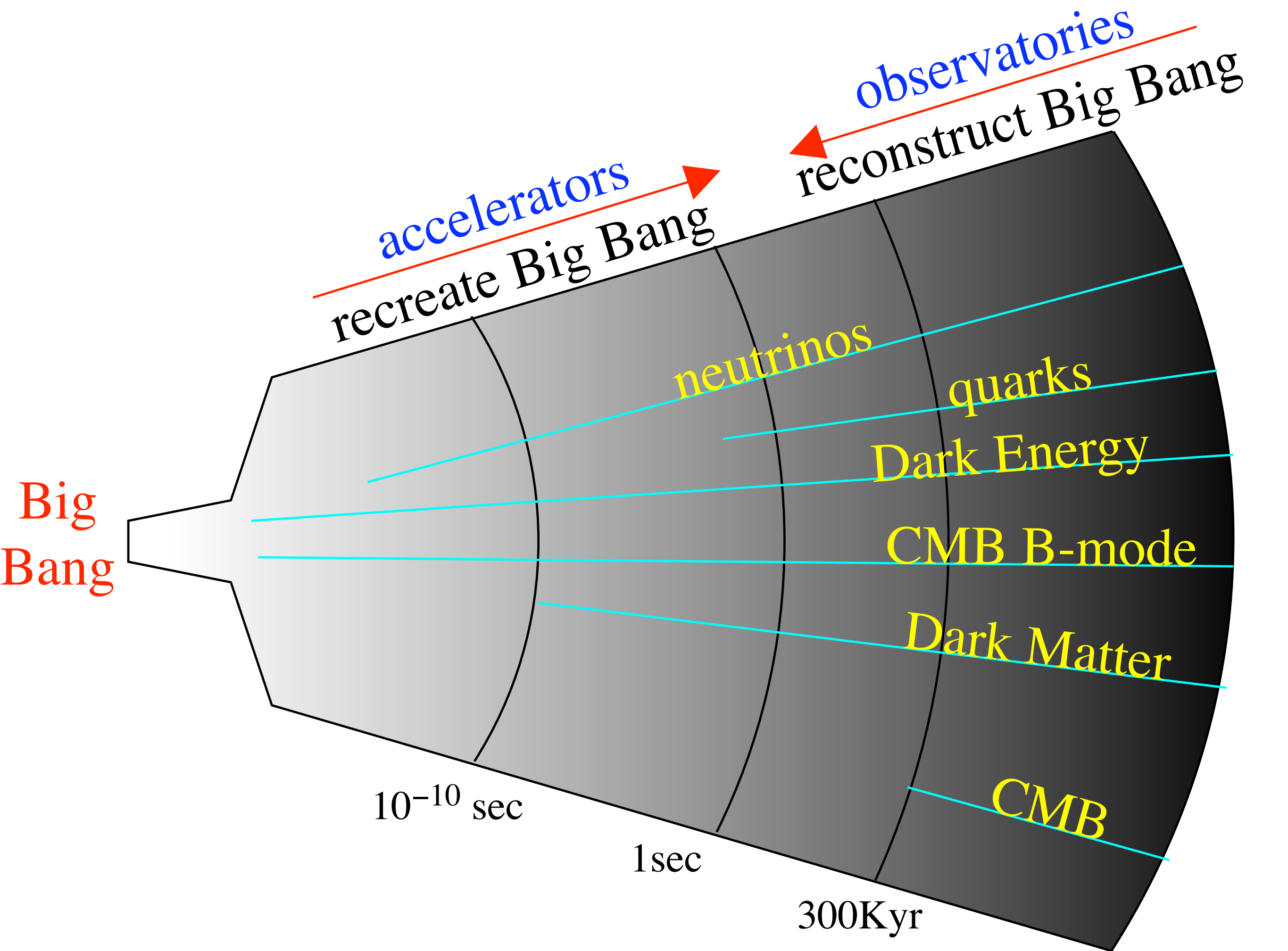
- Near-maximal mixing between  $\nu_\tau$  and  $\nu_\mu$
- Make it  $SU(5)$  GUT
- Then a large mixing between  $s_R$  and  $b_R$
- Mixing among right-handed fields drop out from CKM matrix
- But mixing among superpartners physical

$$\begin{pmatrix} \tilde{s}_R \\ \tilde{s}_R \\ \tilde{s}_R \\ \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{b}_R \\ \tilde{b}_R \\ \tilde{b}_R \\ \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$$



See **leptogenesis** in  $B_d \rightarrow \phi K_S$





# Dark Energy



# Embarrassment with Dark Energy

- A naïve estimate of the cosmological constant in Quantum Field Theory:

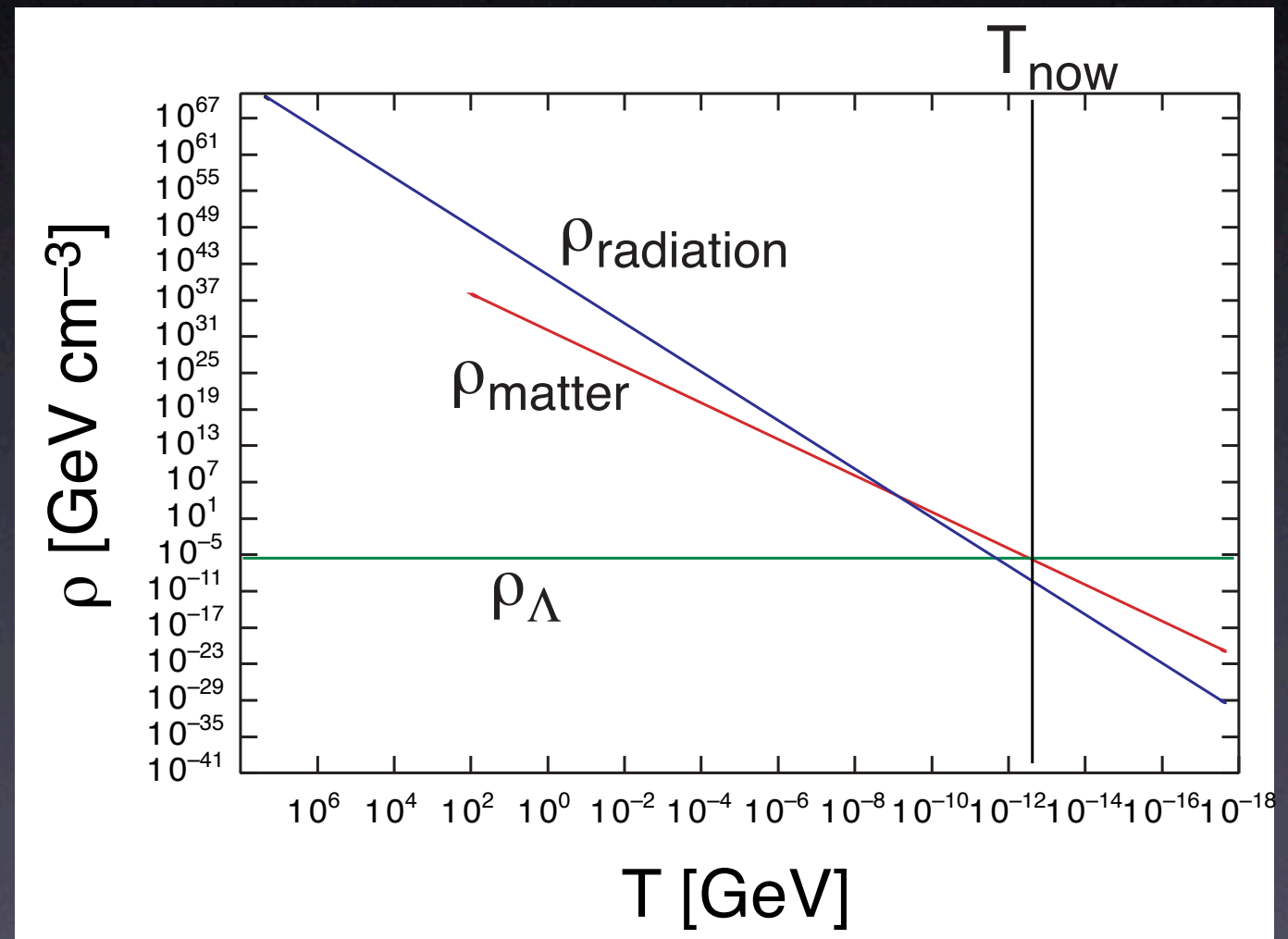
$$\rho_{\Lambda} \sim M_{\text{Pl}}^4 = G_N^{-2} \sim 10^{120} \text{ times observation}$$

The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

# Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- “Why Now” problem
- Actually a **triple coincidence problem** including the radiation
- If there is a deep reason for  $\rho_\Lambda \sim ((\text{TeV})^2/M_{\text{Pl}})^4$ , coincidence natural



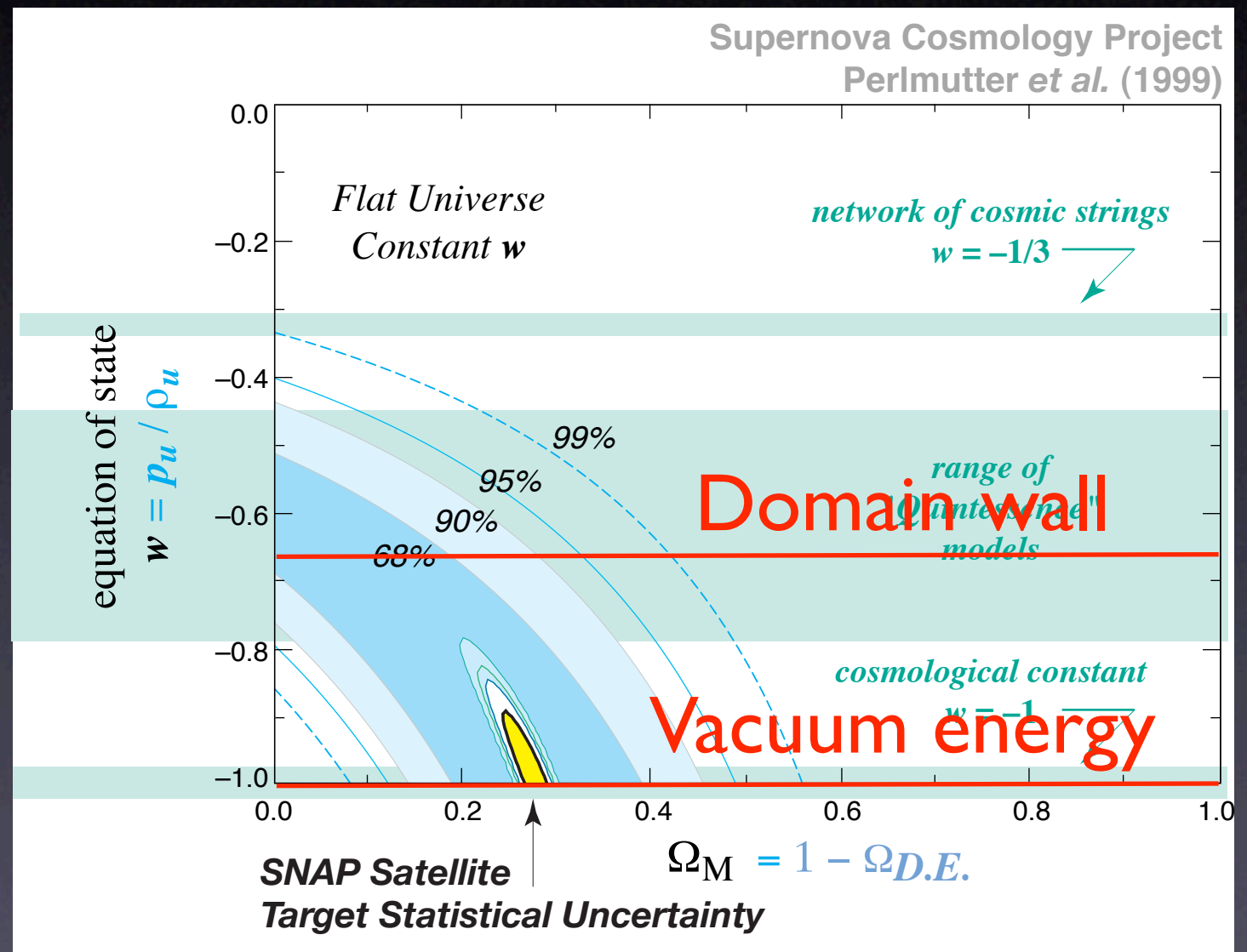
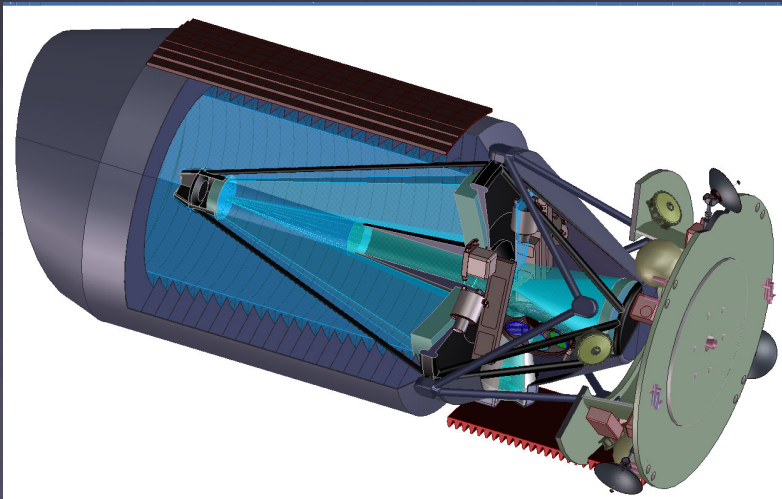


# What is the Dark Energy?

It is a constant?

It is dynamical?

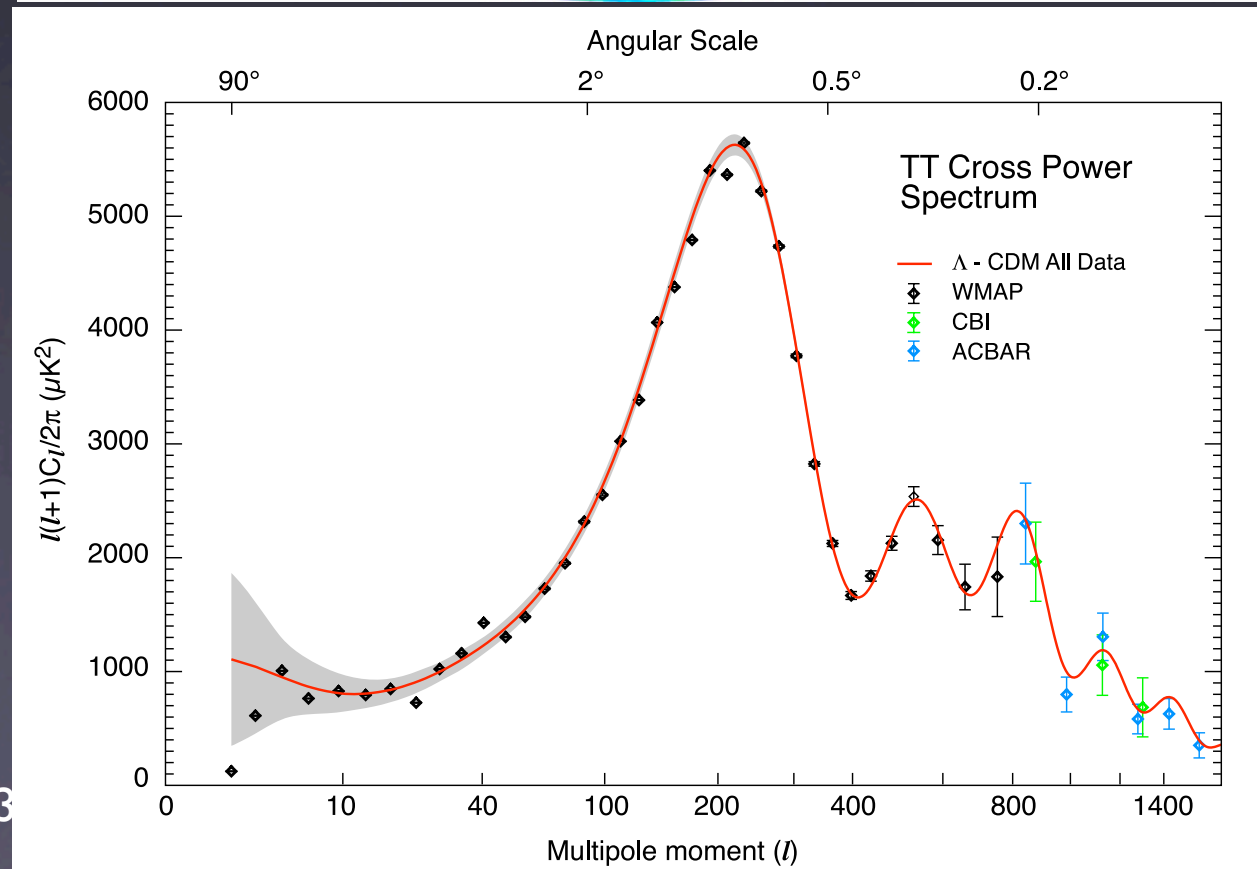
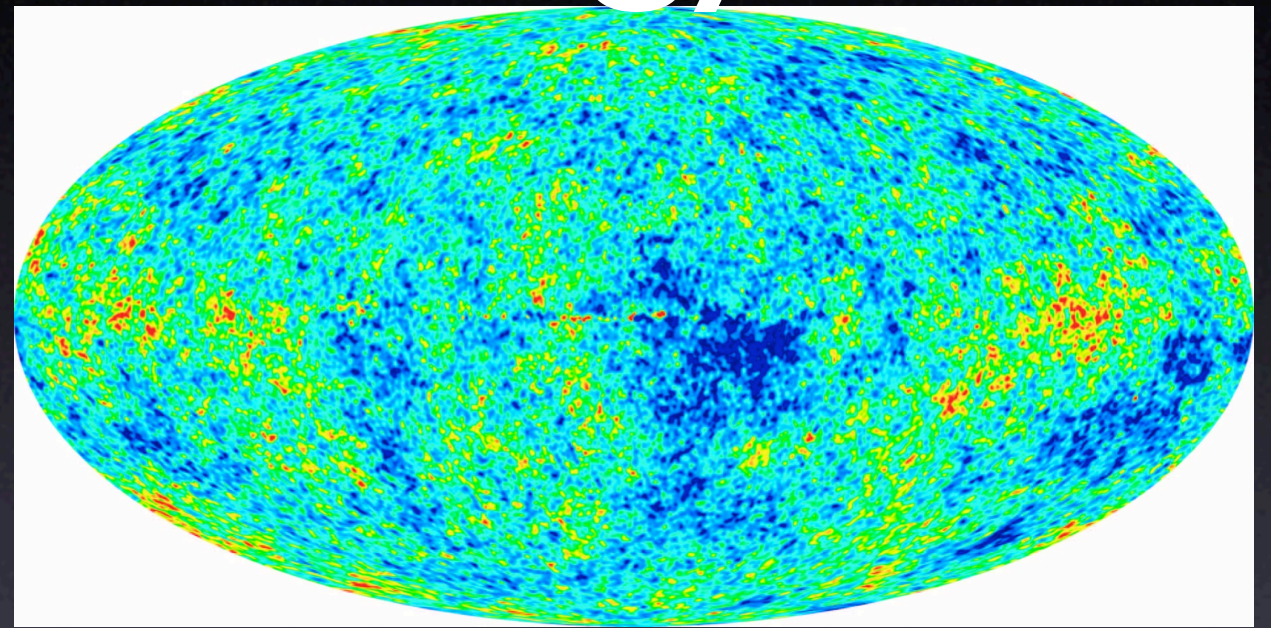
- We have to measure  $w = p/\rho$
- With a dedicated satellite experiment: **SNAP**





# Actually, there once was Dark Energy

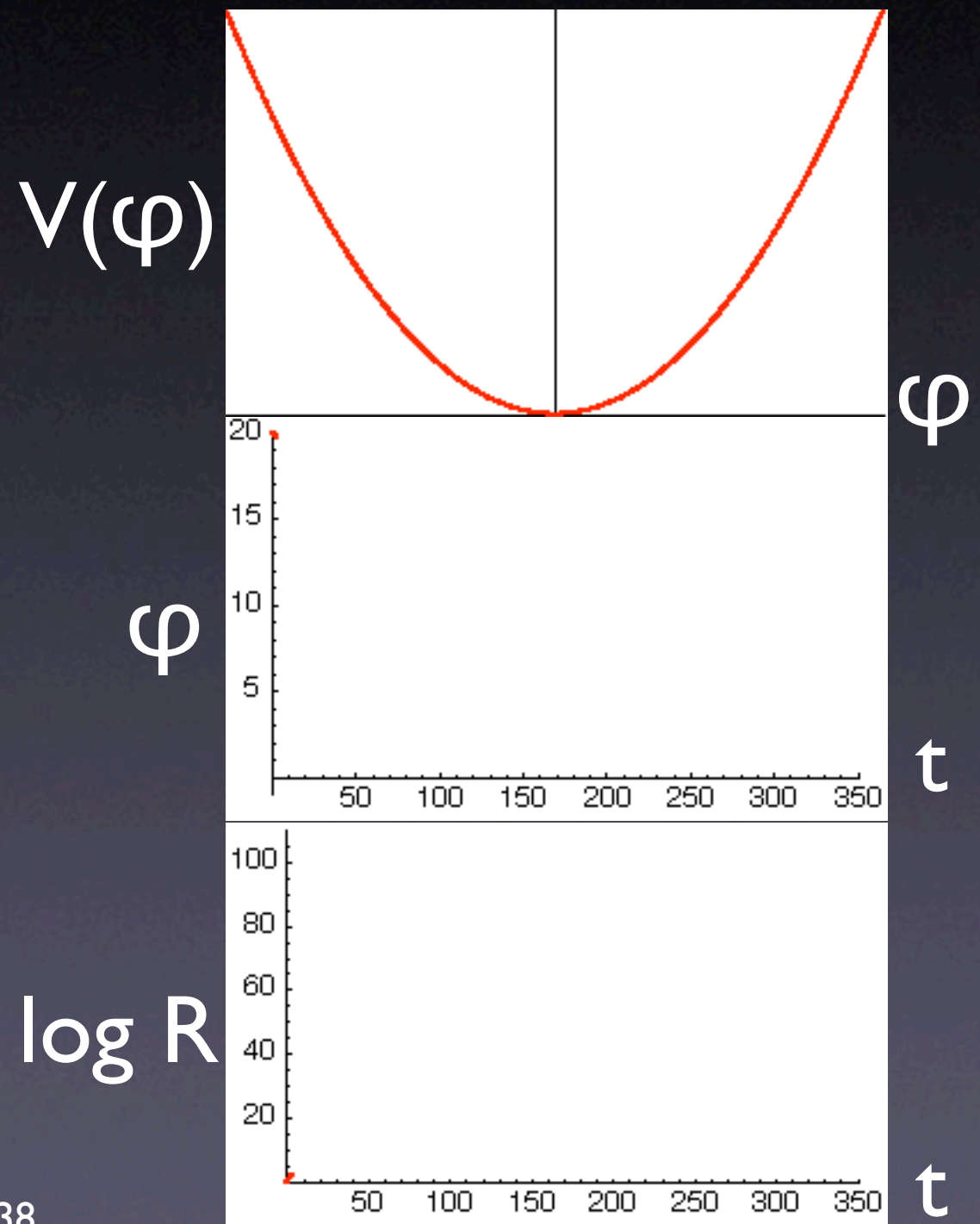
- **Cosmic Inflation** stretched the new-born microscopic space to our entire visible universe
- Observed density fluctuation is due to quantum fluctuation of inflaton
- **E-mode polarization** consistent with this picture





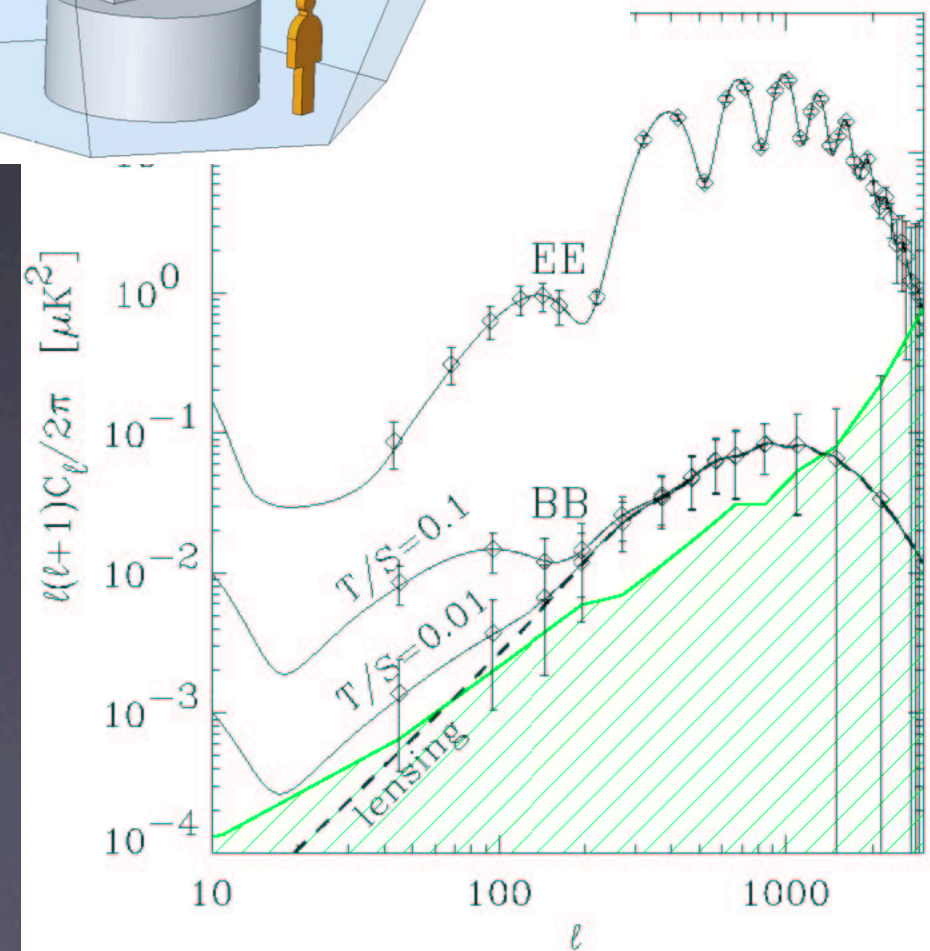
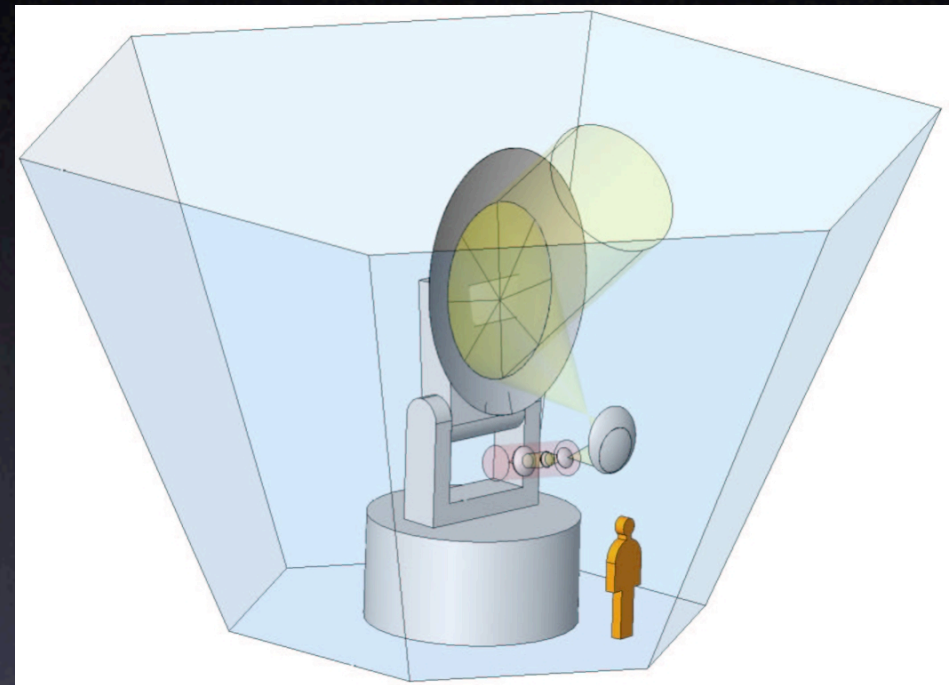
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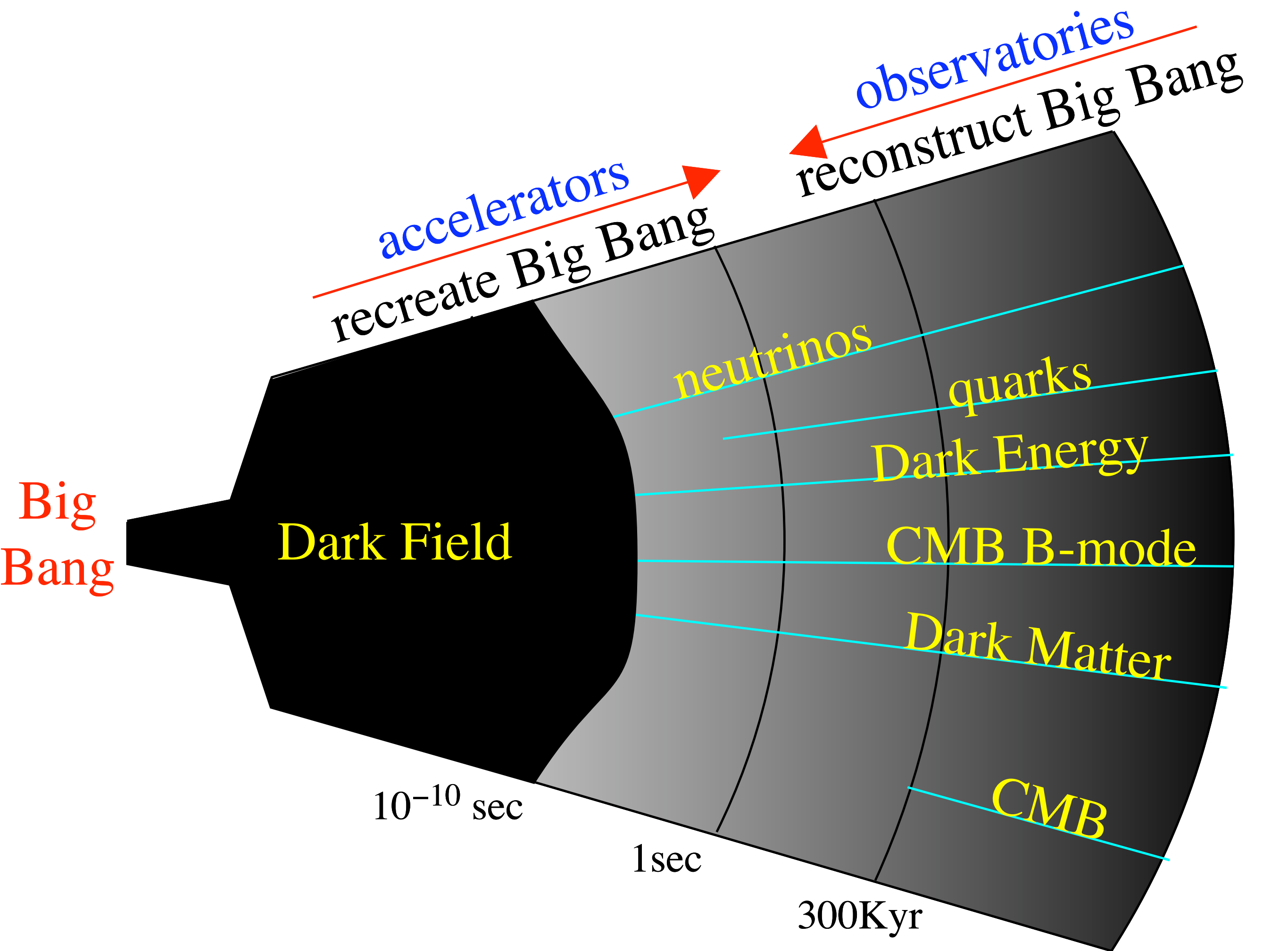


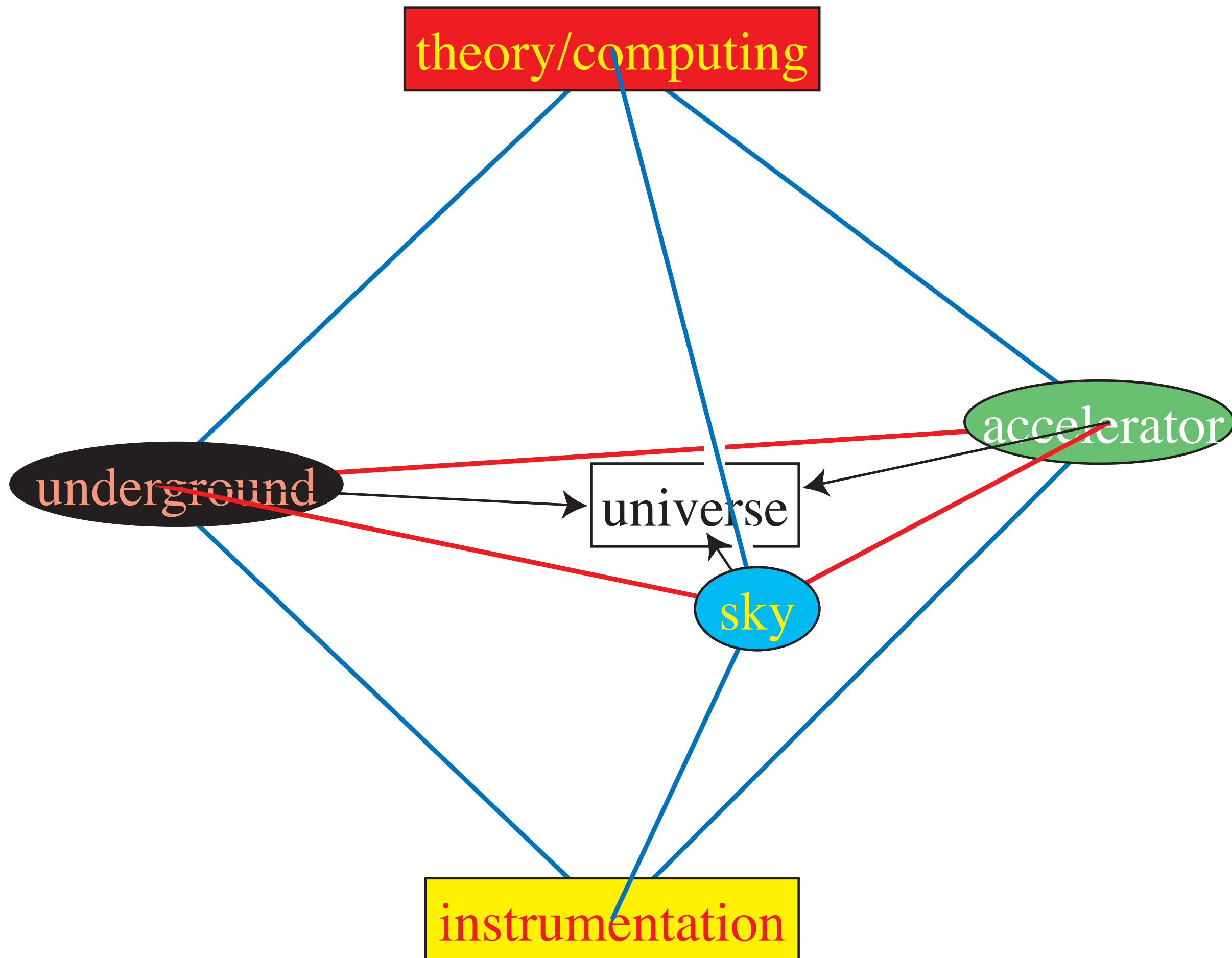
# How do we know it really happened?

- **everything** gets quantum fluctuation, including **gravitons**
- Gravitons from quantum fluctuation gives **B-mode polarization in CMB**
- The size is directly proportional to the **inflationary energy scale**  
 $\Rightarrow$  **POLARBEAR**











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